A GEOGRAPHIC INFORMATION SYSTEM BASED SPATIALLY DISTRIBUTED RAINFALL – RUNOFF MODEL

by

Khalid Naseem Khan

B.E. in Civil Engineering, University of Roorkee, 1998

Submitted to the Graduate Faculty of

School of Engineering in the partial fulfillment

of the requirements of the degree of

Master of Science

In

Civil Engineering

University of Pittsburgh

2002

University of Pittsburgh

School of Engineering

This thesis was presented

by

Khalid Naseem Khan

It was defended on

02/13/2002

and approved by

Dr. C. L. Chiu, Professor, Civil and Environmental Engineering

Dr. T. K. Hung, Professor, Civil and Environmental Engineering

Thesis Advisor: Dr. R. G. Quimpo, Professor, Civil and Environmental Engineering

ACKNOWLEDGEMENTS

I would like to thank my advisor Professor Rafael G. Quimpo for the knowledge, advice and guidance during the course of this research. I would also like to thank Professor Chio- Lin Chiu and Professor Tin-Kan Hung for serving on my thesis' committee. Special thanks to Dr. Uzair M. Shamsi for his time and advise for this research. I am also thankful to Dr. Kathi Beratan, Rene Argueta Jose and Sung-jun Myung of the University Center for Social and Urban Research of the University of Pittsburgh, for their help in this study and data processing. I am also thankful to Dr. Kwabena Odura Asante, whose Ph. D. dissertation helped me define the model.

And last but not the least I would like to thank my parents for their faith and confidence in me without which I would not have completed this course.

ABSTRACT

A GEOGRAPHIC INFORMATION SYSTEM BASED

SPATIALLY DISTRIBUTED RAINFALL-RUNOFF MODEL

Khalid Naseem Khan, M.S.

University of Pittsburgh, 2002

The three important parameters needed to design many hydraulic structures and systems like dams and sewer systems are the flow volume, the peak discharge and the time at which the peak discharge occurs. To estimate these parameters hydrologists develop rainfall-runoff models. Traditionally most of these models assume uniform rainfall distribution and constant watershed characteristics. Though these lumped models are easy to work with and do not require large amount of data and computational time and effort, the results obtained from such models can be improved by working with spatially distributed rainfall and watershed characteristics. In this research such a spatially distributed rainfall-runoff model has been developed. The developed model is based on the time-area histogram method using the source-to-sink routing approach. The SCS (Soil Conservation Service) (now named Natural Resources Conservation Service)

Curve Number data set for the whole watershed is developed using the soil type and land use data. Then based on the curve numbers, the runoff is computed from the precipitation that occurs in the watershed. The amount of runoff being generated in a particular time interval is identified and is used to develop the time-area diagram from which the runoff hydrograph is generated.

The objective was to develop a spatially distributed rainfall-runoff model in which the characteristics of the watershed (represented by the curve numbers) are spatially distributed and also the input to the system (in form of precipitation) is spatially distributed. The curve numbers for the watershed are automatically generated using the soil type and land use data. These curve numbers are then used to compute the runoff being generated in the watershed. Such an approach would remove many limitations of the unit hydrograph method that has been the basis of many traditional rainfall-runoff models.

DESCRIPTORS

GIS

IDRISI

Curve Numbers

Time-area method

Excess rainfall

Runoff

Raster data files

TABLE OF CONTENTS

Page

Page

Page

Page

LIST OF FIGURES

Figure No. Page

Figure No. Page

Figure No. Page

LIST OF TABLES

Table No. Page

CHAPTER 1

1.0 INTRODUCTION

1.1 Overview

The history of hydrology is as old as man himself and so is his desire to control nature. Egyptians dammed the Nile in about 4000 B.C. and archeologists have reported intricate canal networks in Egypt in 3200 B.C. The flow of water on the surface of earth has long perplexed the human mind. The desire to understand the movement of water has mainly arisen from the need to evaluate the amount of water available at a particular location to meet local demand as well as the risk of flooding due to excess water. Hydrologists have always been concerned with the discharge rates and runoff created by rainfall.

The two most important parameters of hydraulic interest are the peak flow and the time to peak. This information is needed for a variety of design applications like dams, spillways and culverts (Ajwaad, 1996)[(1)*]. But most of the rivers are not gauged and even if the gage is in place the record period is too short to estimate the different hydraulic parameters (Muzik, 1993)[(2)] or to predict extreme future events (Ajwaad, 1996)[(1)]. Using historical flow data we can predict future events with a certain return period using frequency analysis. But in the absence of such data we need to develop hydrologic models that would simulate the watershed characteristics and predict the flow rates at any given location in the watershed.

Since the precipitation data is more widely available (because of larger number of gauging stations and the longer record periods) than the stream flow data, many rainfall-runoff models have been developed to estimate the runoff characteristics. The type of model used and the complexity it manifests is contingent to the available data. Hydrologic models try to estimate the watershed response based upon the geo-morphological characteristics of the watershed. The other type of the model can be the empirical model, which works on the mathematical formulas developed using a range of data, which restricts it's use. The Sherman (1932)[3] Unit Hydrograph and regression analysis are the two examples. The physical models on the other hand are based on the physical laws and since they represent the hydrologic process *in situ*, they produce the whole hydrograph and not only the peak flow and the time to peak.

With the increase in the computing power, hydrologists have developed many distributed models. These distributed models have the ability to incorporate information about the spatial variability of the soil, land use, topography, etc. Geographic information systems (GIS) provide an effective tool to handle such huge amount of data. GIS may be used to combine topographical data with other data such as soil types, land use, surface cover, in order to create hydrologic models. GIS have been used in a variety of hydrologic applications like delineating the drainage pattern in a watershed and simulating the surface runoff from flash floods. The drainage time of the watershed can be represented by isochrones, which are lines that divide the watershed into areas with the same time of travel. It can thus be assumed that cells lying in a sub area between two isochrones will have the same travel time to the outlet of the watershed. Using an approach proposed by the SCS, the watershed's response to precipitation can be represented by curve numbers. The curve numbers are an expression of the storage of the watershed based on the soil type and the land use. Curve number values range from 0 to 100. If the value is 0 then no runoff is generated while if the curve number is 100, all the rainfall flows over the surface of earth as runoff without any abstractions or losses.

In rainfall-runoff computation, not only is the generation of excess precipitation spatially distributed but also the precipitation itself. This limits the use of the classic unit hydrograph model (Maidment and Olivera, 1998)[(4)]. This study endeavors to create a model that considers the runoff responses from the watershed on spatially distributed basis instead of being spatially averaged.

1.2 Objectives

The overall objective of this study is to develop a model that incorporates the spatial distribution of the excess rainfall and to study the effect of the grid size resolution of the digital elevation model (DEM) on the runoff hydrograph.

To attain the above objective the following subsidiary objectives need to be satisfied:

1) To automatically generate the isochrones for the watershed under study.
2) To automatically generate the spatial distributed curve number data set.
3) To develop a model that incorporates the spatially distributed curve numbers and precipitation data to generate the runoff hydrograph.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Background

To explain the problem of the availability and the flow of water on the surface of the earth, the hydrologist has an obligation to make the best possible hydrologic estimates, commensurate with the cost and the scope of the incumbent water management problem. Hydrologic calculations are estimates, with the errors in these estimates increasing as the degree of approximation increases. The empirical and approximate nature of the hydrologic estimation methods has led to the development and use of a great number of procedures for estimating runoff. What is required to evaluate the adequacy of a hydrologic procedure is actual hydrologic data. There is no substitute for real, locally applicable data.

The most basic equation in hydrology is the continuity equation, which states that over any time interval for any hydrologic system the difference in the volume of the water entering a system I, and leaving the system, O must equal the change in the volume of water stored in the system, ΔS .

$$I - O = \Delta S \tag{2-1}$$

If the hydrologic system is a small catchment, the inflow to the system would be precipitation. The outflow from the system would be stream-flow, deep seepage and evapotranspiration. Storage within the system would include soil water, ground water, ponds, lakes, reservoirs, channel storage, surface storage, detention storage and interception (Haan et al.,1994)[(5)].

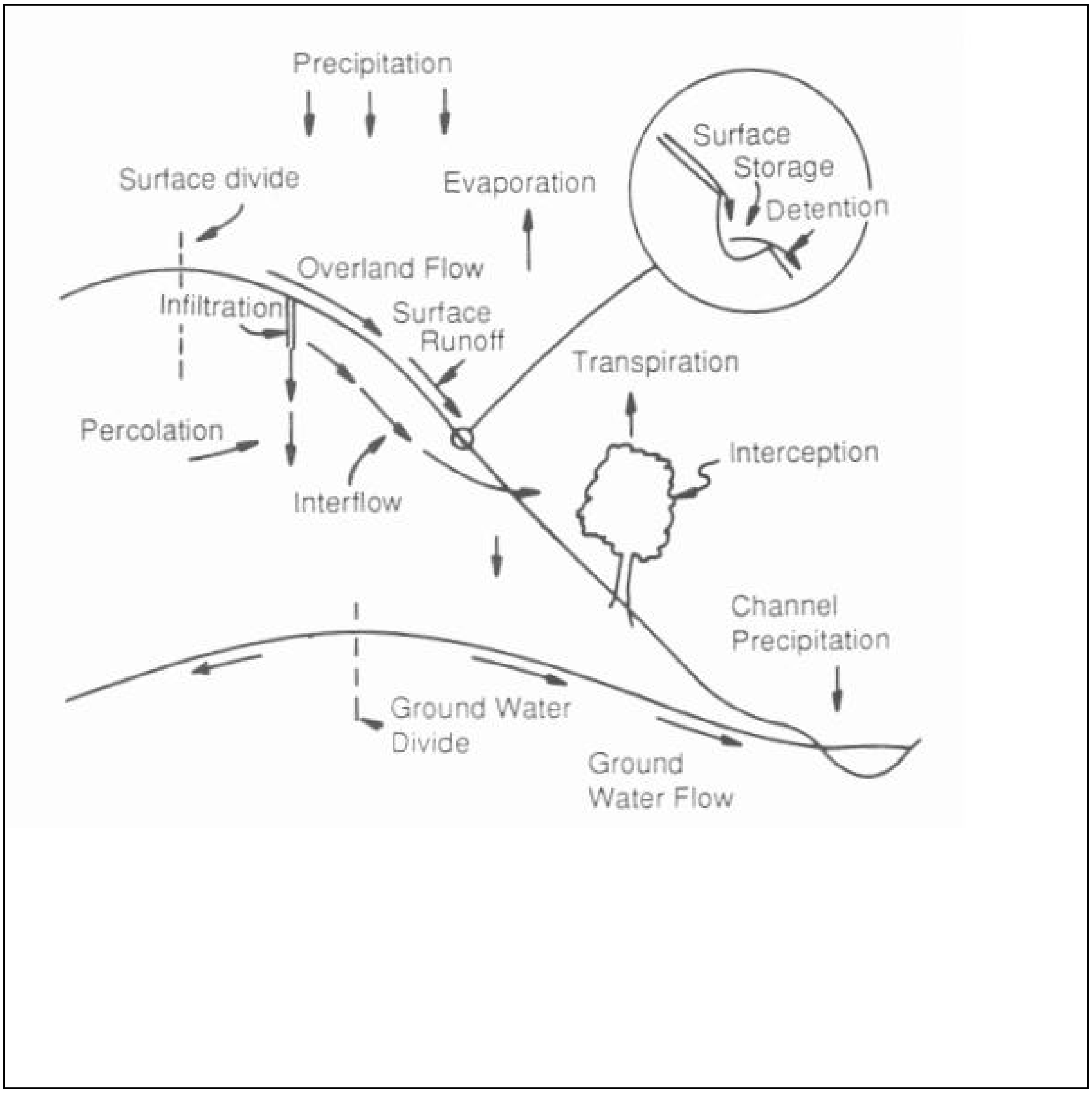

Figure 2-1 Hydrologic Cycle

For short time intervals (hours), evapotranspiration and deep seepage can be generally ignored. For long time intervals (weeks), surface storage, surface detention, and interception can often be ignored. In the absence of ponds, reservoirs or lakes the hydrologic equation can be further simplified.

2.2 Modeling the River Basin

A conceptual model that can be applied to all hydrologic systems is the control volume, proposed and defined by Chow et al (1988)[6] as

"a structure or volume in space, surrounded by a boundary, that accepts water and other inputs, operates on them internally, and produces them as outputs".

Modeling a system means establishing a relationship between the input to the control volume and the output that it produces. The input, the system response function that transforms the input to produce the output, the output and the control volume are the components in the modeling of a hydrologic system. The very first requirement of modeling is defining a control volume. According to Asante (2000)[7] the most common of these can be grouped into three classes as described below.

2.2.1 The Watershed Based Approach

In this approach the hydrologic system is made up of rivers and the areas draining into these rivers. Several features are used to describe this approach, like reaches, watersheds, junctions, diversions and man made features like dams, reservoirs and canals. A reach is defined as the stretch of a river in which no major tributary joins it. The area of land draining directly into a reach forms its watershed. Junctions are locations where two or more reaches meet. Diversions are locations where a single reach divides to form two or more reaches downstream. In the watershed approach all these features are regarded as individual control volumes which have their unique response functions to transform the inputs into downstream discharges. All these control volumes are linked together so that flow from one control volume can be passed into another control volume till it arrives at a terminal point or an outlet. The Hydrologic Modeling System (HMS) developed by the Hydrologic Engineering Center of the US Army Corps of Engineers (Peters et al., 1998)[8] is an example of such a model.

2.2.2 The Cell to Cell Routing Approach

In this approach the land surface is divided into smaller segments and flow from one segment is routed to the next segment till it reaches the terminal point. For convenience and computational cost and efficiency, the segments are divided into equal sized cells and hence the name cell-to-cell routing. However this approach can be applied to irregular land segments with equal accuracy. Assuming homogeneity in the land segments the need to distinguish between the overland flow and in stream flow processes can be dispensed. In this approach each cell is regarded as a control volume. Flow from each cell is routed to the next cell using a unique response function. This response function captures the effect of various flow processes occurring within the control volume. The growing usage of this approach can be attributed to the need of combining the land surface models with the models of the atmospheric and sub surface flow phases of the hydrologic cycle.

2.2.3 The Source to Sink Routing Approach

In this approach the land segment is divided into smaller segments and flow from each segment is routed directly to the terminal segment or the outlet. In this approach the flow path linking each segment to the outlet forms a control volume. The system response function transforms the input of each segment as it flows into the outlet. The system response function also accounts for the losses occurring in the flow path. The flow path may be composed of different flow regimes like overland flow and in stream flow in which water may flow at different velocities. The response function for each flow path summarizes all the transformations that occur along a flow path between the source of input and the discharge location (the outlet or the sink). The name "source-to-sink" routing is used by Olivera et al (2000)[9] to describe all models of this type. An example of such a model is the Clark Unit graph method (Clark, 1945)[10].

2.3 Methods of Characterizing Flow

Having decided the control volume for modeling the river basin, the next step is to define the flow routing process and the nature of the system transformations used to characterize these processes. The transformations may be translation, redistribution and translational losses. Translation involves the simple movement of the water from the source to the sink. During the translation the shape of the input pulse may change because of three mechanisms. The first mechanism is the shear force between the water and the channel surface it comes in contact with. The second mechanism involves the off-stream storage created by the changing dimensions of the channel and the passing of water through water bodies like lakes and reservoirs. The third mechanism is the loss of flow through seepage and evaporation. The first two mechanisms can be combined as one and called redistribution. According to Asante[7] following are the three type of flows.

2.3.1 Translation with Incidental Dispersion

The simplest form of routing involves describing the movement of water through a control volume using a continuity equation and the mathematical equation between the discharge and the storage of the control volume. There is no factor accounting for the redistribution, which is achieved as a by-product. The methods are referred as level pool routing. The most commonly used of these methods is the linear reservoir method.

2.3.2 Translation with an Approximate Dispersion Process

These methods contain a factor that controls the dispersion experienced by the input passing through the control volume. The Muskingum method is one method that falls in this category in which the Muskingum parameter x is used to describe the dispersion experienced by the input.

2.3.3 Translation with Fully Described Dispersion

These methods rely on the momentum equation for unsteady, non-uniform flow (Chow et al,1988)[11].

$$\frac{\partial V}{\partial t}+\frac{V\partial V}{\partial x}+g\left(\frac{\partial h}{\partial x}+S_f\right)=0 \qquad (2\text{-}1)$$

where

V is the flow velocity

S_f is the frictional slope

$\frac{\partial h}{\partial x}$ is the slope of the head

x is the distance along the longitudinal direction

t is the time

The momentum equation describes the change in the form of the input subjected to the friction and gravity forces. Since these are the same forces that deform the input as it passes through the control volume this equation in effect describes the dispersion process. For flow routing the momentum and continuity equations together, are referred to as the St. Venant equations after the 19th century French mathematician who derived them in 1871. The continuity equation is

$$\frac{\partial (AV)}{\partial x}+\frac{\partial A}{\partial t}-q=0 \qquad (2\text{-}2)$$

where

$\frac{\partial (AV)}{\partial x}$ is the rate of change of flow rate with distance

$\frac{\partial A}{\partial t}$ is the rate of change of area of flow with respect to time

q is the lateral inflow or outflow along the channel

There is no analytical solution for these equations in complete form. Some simplifying assumptions need to be made for the equations to be solved. The assumptions and their resulting solutions can be classified into three categories, namely dynamic, kinematic and diffusion wave solutions.

In dynamic wave routing, the full St. Venant equations are used but assumptions are made about the condition of flow at the boundaries. Kinematic and diffusion wave routing on the other hand make assumptions about the condition of flow parameters. These assumptions allow one or more terms in the momentum equation to be dropped thus making the analytical solution of the St. Venant equation possible. It assumes that within the control volume the velocity is constant in time and space, and that the water surface is parallel to the channel bed (Chow et al, 1988)[12]. The diffusion wave routing differs from the kinematic wave routing in that it does not assume a constant water depth in the control volume. This assumption about the time invariant velocity is a big limitation of the solutions because in real streams large flows are translated faster than smaller flows.

2.4 Predicting the Runoff

The absence of the gages in most watersheds gave birth to the necessity of developing the rainfall runoff models which were required to establish the hydraulic parameters of the peak flow and time to peak, which are the most important parameters for the design problems.

According to Todini(1988)[13] the rainfall runoff modeling started in the second half of the nineteenth century mainly to address the following three engineering problems, namely:

1) Urban sewer design

2) Land reclamation drainage system design

3) Reservoir spillway design

Hydrologists started by applying the empirical equations developed for a particular region to other areas assuming that the conditions were "close enough" (Todini, 1988)[13]. The rational method developed for small watersheds on the basis of land use and rainfall intensity was the first rational attempt to predict runoff from rainfall (Todini, 1988)[13]. To apply the fundamentals of the rational method to larger watersheds the isochrones method was developed which produced more realistic and accurate solutions (Todini, 1988)[13]. Sherman[3] was the first to introduce the concept of the Unit hydrograph based on the theory of superposition. He defined the unit hydrograph as:

" If a given one-day rainfall produced a 1-in depth of runoff over a given drainage area, the hydrograph showing the rates at which the runoff occurred can be considered a unit graph for that watershed."

Synder[14] in 1938 developed the first standard unit hydrograph procedure called the synthetic unit hydrograph. This synthetic unit hydrograph can be used to develop unit hydrographs anywhere on a stream in the same watershed. Clark[10] in 1945 developed a synthetic unit hydrograph using the instantaneous unit hydrograph and the time-area curve. The isochrones divide the watershed into area with equal time of travel to the outlet and hence the time area curve is obtained. The unit hydrograph can be worked out from this time area curve. According to Clark the discharge at any point is a function of the translation and the storage characteristics of the watershed (Al-Medeij, 1998)[15]. The Soil Conservation Service in 1957 developed a SCS method based on a dimensionless hydrograph. It works on the assumption that a unit hydrograph can be approximated by a triangle. It uses curve numbers for calculating the runoff. Curve numbers define the physical parameters of the watershed. In 1973, US Corps of Engineers launched HEC-1. This package produced a synthetic unit hydrograph using the Clark's method among others. In the absence of the time area curve it was suggested to use a dimensionless time area curve equation.

$$AI=1.414\ T1.5 \quad 0<=T<0.5 \tag{2-3}$$

$$1-AI=1.414(1-T)1.5 \quad 0.5<=T<1 \tag{2-4}$$

where AI is the cumulative area as a fraction of total sub-basin area and T is the factor of time of concentration.

With the increased power of the computers and the advent of GIS, the hydrologic models made a move from the lumped systems to spatially distributed systems. Grid based GIS appears to be a very suitable tool for hydrologic modeling, mainly because "raster systems have been used for digital image processing for decades and a mature understanding and technology has been created for that task"(Maidment, 1992)[16]. Grid systems have proved to be ideal for modeling gravity driven flow, because a characteristic of this type of flow is that flow-directions depend entirely on topography and not on any time dependent variable (Maidment, 1992)[16]. Hill et al.[17] in 1987 used GIS with remotely sensed data in the Watershed Hydrology Simulation (WAHS) model (developed by Singh and Aminian in 1985)[18]. LANDSAT MSS satellite information was used to produce land cover and land use map layers and the SCS curve numbers using GRASS, a raster based GIS (Smadi, 1998)[19]. Stuebe and Johnston (1990)[20] established runoff using the SCS Curve Number method manually and by using GRASS. It was found that GIS made the estimations easier while dealing with large areas (Al-Medeij, 1998[15] and Smadi, 1998[19]). Moeller[21] in 1991 used GIS to derive spatially weighted hydrologic parameters (percent imperviousness and CN values) to be used in HEC-1.

In 1992, Bhaskar, Janes and Devulapalli[22] simulated runoff using the Geomorphological Instantaneous Unit Hydrograph (GIUH). Arc/Info GIS was used to establish the watershed parameters. They used the hydrologic model WAHS. In their study total volume of runoffs showed good agreement but the peak flow rate occurred much later than the observed values (Al-Medeij, 1998[15] and Smadi, 1998[19]).

In 1994, Mark Michelini[23] developed a method for the automatic generation of an unit hydrograph using the time area curve. Fortran codes were written to process the digital elevation model (DEM) and estimate the different watershed features and a raster based GIS IDRISI was employed for the image processing and visualization purposes. His case study of " Short Run Ellisburg Project Pennsylvania " produced excellent results. The only assumption in Michelini's method was the curve number for the watershed. Michelini's method was verified by Bodnar[24] in 1995 using real field data. He concluded that by using GIS, the amount of subjectivity is greatly reduced and the results can be generated in a fraction of the time it would have taken if the same analysis were carried out manually.

In 1996 Zollweg et al.[25] developed an integrated soil-moisture based rainfall-runoff model (SMoRMod) in GRASS.

In 1998 Evans, Peters and Brunner[8] from the US Army Corps of Engineers proposed the hydrologic modeling system (HEC-HMS) which was an improvement of the flood hydrograph package (HEC-1). HEC-HMS was updated with the ModClark module the same year, which incorporated the use of the radar sensed precipitation data into the rainfall runoff modeling.

Al-Medeij, in 1998, undertook the task of removing the subjectivity from Michelini's model but estimating the curve number for the watershed.

2.5 Unit Hydrograph

The unit hydrograph is the unit pulse response function of a linear hydrologic system (Chow et al., 1988)[(26)]. The unit hydrograph method is derived from the fundamentals of the linear system analysis. The unit hydrograph is based on the principle of superposition and the principle of time invariance. If the principle of superposition were not to hold then the runoff hydrograph for a complex storm could not be generated using a series of hydrographs, which in turn are generated using the unit hydrograph with a number of lagged rainfall excess volumes. On the other hand, if the principle of time invariance were not to hold good then the predictions based on the past observations would never turn out to be true, because every other input would produce a different response as it would be undergoing a different transformation and hence these responses cannot be superimposed.

The unit hydrograph is generated for a particular time base, which remains constant regardless of the volume of runoff produced by a storm of the same duration. The unit hydrograph can be used to generate the runoff response of a storm with depth other than unity simply by multiplying the runoff depth of the storm by the ordinate of the unit hydrograph, the only condition being the duration of the storm and the unit hydrograph used have to be the same.

2.5.1 Limitations of the Unit Hydrograph Method

The unit hydrograph method has some inherent assumptions which limit it's use:

1) *The excess rainfall has a constant intensity within the effective duration.*

Only short duration storms would qualify on this criteria as they are expected to produce a constant rate of excess rainfall, yielding a single peaked hydrograph.

2) *The excess rainfall is uniformly distributed throughout the whole drainage area.*

This may limit the application of the unit hydrograph for a large watershed which might not have an uniform distribution of the excess rainfall, in which case one may have to divide the large watershed into smaller sub-basins for analysis.

3) *The base time of the direct runoff hydrograph (duration of the direct runoff) resulting from an excess rainfall of given duration is constant.*

The duration of the direct runoff hydrograph is in fact a function of the base flow separation technique. This assumption implies that the unit hydrograph method would provide different responses for different rainfall intensities.

4) *The ordinates of all direct runoff hydrographs of a common base time are directly proportional to the total amount of direct runoff represented by each hydrograph.*

Since the field data is not linear when we use them for the calculation of the runoff they provide approximate results because the principle of superposition is not satisfied entirely.

5) *For a given watershed, the hydrograph resulting from a given excess rainfall reflects the unchanging characteristics of the watershed.*

Since the unit hydrograph is representative of the watershed characteristics it would stop providing satisfactory responses if these characteristics were to change, namely the soil type and land use conditions, the channel conditions or the storage conditions.

Since the response of the watershed to the excess rainfall depends on the watershed characteristics like the slope, area and the shape, the unit hydrograph generated for one watershed can be used for another watershed just by comparing their characteristics. But the traditional unit hydrographs fail to respond to the changes in the characteristics of the watersheds and the variability (both spatial and temporal) of the excess rainfall. It is this limitation of the unit hydrograph theory that inspired this study.

2.5.2 Unit Hydrograph (UH) and the Instantaneous Unit Hydrograph (IUH)

The unit hydrograph is the plot of the flow rate generated by unit excess rainfall versus time. This unit excess rainfall is assumed to be generated uniformly over the watershed with an uniform intensity for a given time interval. Thus an H-hour unit hydrograph is defined as a hydrograph of direct runoff having a volume of one inch resulting from an H-hour storm having a net rainfall intensity of 1/H inch/hour (Quimpo, 1996)[27]. The unit hydrograph is only good for a given rainfall duration and watershed.

If the excess rainfall is of unit amount and the duration is infinitesimally small the resulting hydrograph is an impulse response function and is called the instantaneous unit hydrograph. For the IUH the excess rainfall is applied to the watershed in zero time. This is only possible in theory but it is important as the IUH characterizes the watershed's response to the rainfall without reference to the rainfall duration (Chow et. al, 1998)[28]. In other words it is an expression for the geomorphology of the watershed (the hydraulic length, slope, shape, surface roughness, etc.).

If a system receives a unit input and it is applied instantaneously at time t , the response of the system at a later time t is given by the unit impulse response function $u(t-t)$, where $t-t$ is the lag since the impulse was applied. That is to say that a storage reservoir is initially empty and is instantaneously filled with water of unit amount the resulting outflow function is the impulse response function. In the figure 2-2, the amount of input between time t and $t+dt$ is $I(t)dt$. For example if $I(t)$ is the precipitation intensity in inches per hour and dt is the infinitesimal time interval measured in hours, then $I(t)dt$ is the depth of the rainfall in inches input into the system. The direct runoff resulting after time $t-t$ is $I(t)u(t-t)dt$. The response to the complete input function $I(t)$ can be found by integrating the response. This integral is known as the convolution integral.

$$Q(t) = \int_0^t I(t)u(t-t)dt \tag{2-5}$$

For the IUH the this integral has the following properties:

$$l = t - t$$

$0 \le u(l) \le \textit{some positive peak value}$ for $l > 0$

$u(l) = 0$ for $l \le 0$

$u(l) \to 0$ for $l \to \infty$

$\int_0^\infty u(l)dl = 1$ $\int_0^\infty u(l)ldl = t_L$

where t_L is the lag of the IUH.

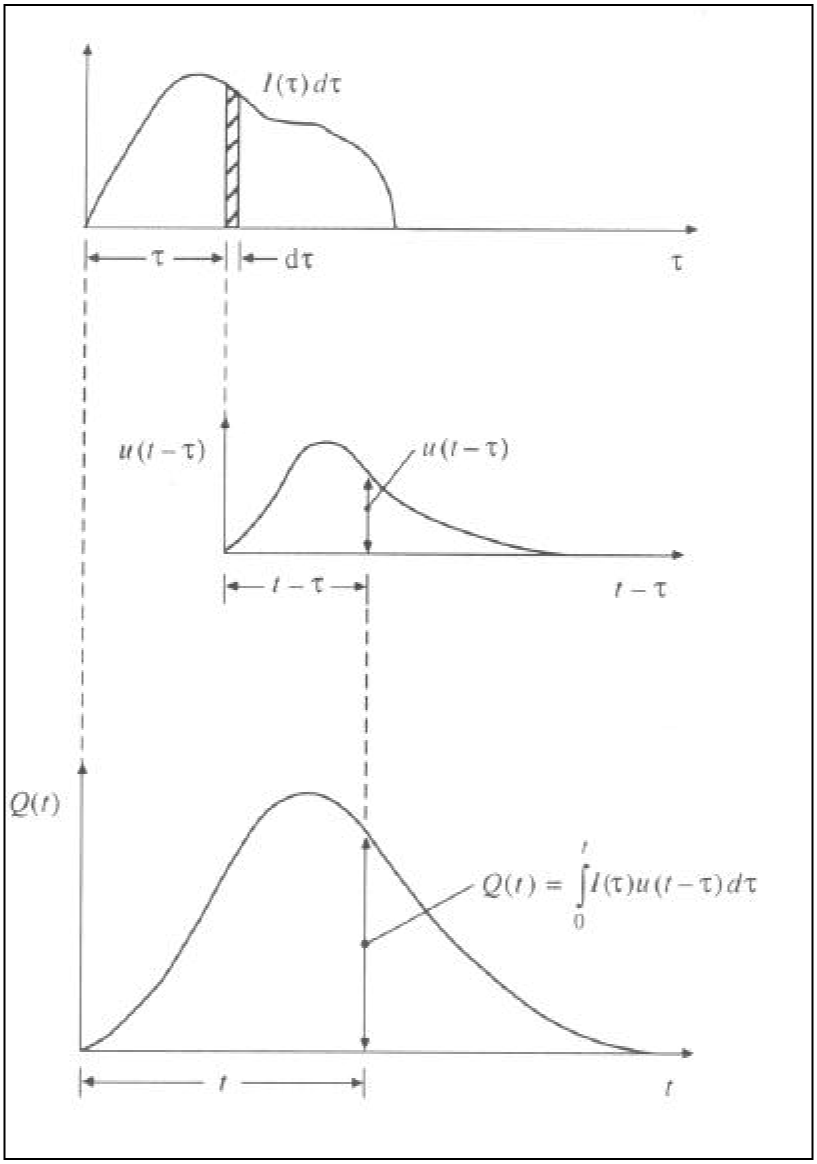

Figure 2-2 Continuous Time Function

2.5.2.1 Relationship between IUH and UH.

The IUH can be converted to a unit hydrograph of a particular duration. The ordinates of the T-hour unit hydrograph can be obtained by averaging the ordinates of the IUH at successive T-hour interval.

Let u(t) be the impulse response function (IUH)

g(t) is the unit step response function (S-curve)

h(t) is the discrete pulse response function (T-hour unit Hydrograph)

By definition:

$$g(t) = \int_0^t u(t-t)dt = \int_0^t u(l)dl \quad \text{if } l = t - t \tag{2-6}$$

And therefore : $u(l) = \frac{d}{dt} g(t)$

By definition the T- hour unit hydrograph is :

$$h(t) = \frac{1}{T}[g(t) - g(t-T)] \quad , T = \Delta t \tag{2-7}$$

The impulse response function *u(t)* can be approximated by the finite difference expression for the first derivative.

The backward difference gives :

$$u(t) = \frac{d}{dt} g(t) = \frac{g(t) - g(t - \frac{T}{2})}{\frac{T}{2}} \tag{2-8}$$

The forward difference gives :

$$u(t-T)=\frac{d}{dt}g(t)=\frac{g(t-\frac{T}{2})-g(t-T)}{\frac{T}{2}} \quad \text{(2-9)}$$

The average of the forward and the backward difference gives

$$\frac{u(t)+u(t-T)}{2}=\frac{1}{T}\left[g(t)-g(t-T)\right] \quad \text{(2-10)}$$

which is the same as the discrete pulse response function *h(t)* or the T-hour unit hydrograph. Thus, by averaging the successive ordinates of the IUH we can obtain the unit hydrograph ordinates.

CHAPTER 3

3.0 METHODOLOGY

3.1 INTRODUCTION

This chapter provides an overview of the methodology that has been employed to accomplish the objectives stated in the introduction. It also presents the assumptions that are inherent in the model that has been employed namely, the Source to Sink (STS) model as stated in the literature review.

3.1.1 Study Overview

In order to accomplish the objectives of this study, a spatially distributed runoff hydrograph model was generated which is dependent only on the digital elevation model (DEM) and soil type and land use data for input. The soil type and land use data are used to create a curve number raster file which contains the spatial distribution of the curve numbers manifesting the varied nature of the watershed characteristics.

The Digital Elevation Model (DEM) is the very basic data that is required to start the processing of a watershed. A DEM can be defined as a database or a file that contains the elevation data in digital form that describe the topological surface of an area. The watershed response to precipitation can be attributed to curve numbers. The curve numbers define the storage effect of the watershed based on the soil type and the type of land use. Curve number values range from 0 to 99. If the value is 0 then no runoff is generated while if the curve number is 99 all the rainfall flows over as runoff without any abstractions or losses.

The model is essentially a variation of the Clark's time area method. The cumulative time of travel of the excess rainfall is computed from the source (individual point in the watershed) to the sink (the outlet of the watershed) and is routed through the topography of the watershed. Based on the time of travel for each source the isochrones are developed and then the time-area histogram is derived. The time area curve thus developed is used to develop the runoff hydrograph.

3.1.2 Developing the Model

The spatially distributed runoff hydrograph model was developed using Fortran codes for the processing of the DEM and other raster files. A GIS software, IDRISI is employed for the image processing and visualization. IDRISI is a geographic information and image processing software developed by the Graduate School of Geography at Clark University. It is competent both in the raster and the vector data types but in this study only the raster data types have been used. The reason for working with raster data type is that it is easier to manipulate it using external programming and it possesses more analytical power when compared to the vector data type. The other reason is that, mathematical combinations of the raster image files are fast and accurate. Also, since the calculations are being carried out cell-by-cell one can keep track of the process being simulated.

The model uses the built-in commands or modules of the software for the pre-processing of the DEM for generating the watersheds and the stream network. Specialized Fortran codes manipulate the different raster files created to determine the flow path and the travel time from each source in the watershed to the outlet. The travel time for each of the individual sources are summed to get the cumulative time of travel for the sources. Once all the sources present in the watershed are processed the cumulative time of travel is divided into intervals to work out the isochrones by identifying which sources fall in a particular time interval. The program counts the number of cells that fall in each time interval to generate the time area curve. It also calculates the total excess rainfall generated in the time intervals which is used to create the time-runoff histogram which can be converted into a runoff hydrograph using an appropriate routing technique.

3.1.3 Lumped versus Distributed Models

Traditionally all the models developed by hydrologists were meant to be used considering the hydrologic system to be lumped. In the lumped model the system is spatially averaged such that all the characteristics of the system are given an average value disregarding their areal distribution in the system. Lumped systems cannot account for the spatial variability of the characteristics of the watershed like soil type and land use and tend to use the average value. For example in the lumped model, the watershed is assumed to receive a uniform precipitation overlooking the internal spatial variation of watershed precipitation (Chow et al., 1988)[(29)]. They also tend to use the average value of the curve number, which is the representation of the watershed's storage characteristics.

On the other hand, the distributed system considers the spatial variability of the characteristics of the watershed and takes into account the areal distribution of the characteristics like the soil type and the land use. The distributed model considers the hydrologic processes occurring at the various places in space and defines the different model parameters and inputs taking into account their spatial variability (Chow et al., 1988)[29].

Though the distributed models produce better results, they require a large amount of data and processing time and effort. Until the 1980's due to the exorbitant cost of the computation process, the hydrologists settled for the lumped models. But with the advent of fast computers and software like GIS, the distributed models have gained popularity.

This study also is an endeavor to switch from the lumped model to the distributed one. It takes into account the spatial variability of the precipitation in the watershed and also the watershed characteristics like the curve number, which affects the amount of excess rainfall that forms the runoff.

3.1.4 Assumptions in the Model

3.1.4.1 Linearity. A hydrologic system may be classified by the nature of it's transformation as linear or non-linear. The system is said to be linear if it's transformations meet the criteria for the application of super-positioning. Otherwise, it is a non-linear system. As Dooge(1973)[30] points out, mathematically linearity may be defined as

"If a transformation X1(t) results in Y1(t) and X2(t) results in Y2(t) then for a linear system, X1(t)+X2(t) results in Y1(t)+Y2(t)"

An assumption of linearity is made in the source-to-sink routing model. In other words the decomposition of the inputs at the source into a series of smaller segments results in an identical output at the sink as would result from a routing the lumped input. The assumption of linearity allows the longitudinal decomposability of rivers into smaller segments which can be modeled separately, and also areal decomposability which allows basins to be subdivided and modeled as a series of separate watersheds, and super-positioning the sub-area responses which allows the results of simulations in different watersheds to be aggregated. The assumption of linearity has been widely used in hydrology and it underlies many routing methods such as unit hydrographs, the Muskingum method, etc.

3.1.4.2 Time Invariance. The second important assumption made in the source to sink approach is that the transformation parameters relating system input to the output are time invariant. In other words, a given system input would result in the same output irrespective of the time of application of the input. For a source to sink model, this implies that the physical location of the flow path linking a source and the sink does not vary with time. In addition, the parameters at each location along the flow path remain constant throughout the routing period. According to Dooge(1973)[30] time invariance can be expressed mathematically as follows;

" If transformation X(t) results in Y(t) then for a time invariant system, X(t+r) results in Y(t+r) where t and t+r are points in time."

This assumption is essential to the definition of a system transformation if it to be applied to subsequent events. If a system transformation changes with time then the outputs due to two events occurring within a few minutes of each other cannot be superimposed because they undergo different transformations. Hydrologic systems depend upon the principle of time invariance of the parameters to predict the output of future events. If a system transformation is time variant then no relationships can be deduced from the past events and consequently no predictions can be made for the output of future events.

3.1.5 STS Model Routing

In the source to sink modeling, a river basin is viewed as a series of sources each defined and parameterized not in relation to neighboring cells but in relation to an observation point or sink located further downstream. Sources interact with the sink through a response function. The model is not fully spatially distributed in the sense that the location of water is not tracked throughout the system. Rather, water is provided as input at the source and only measured as it flows into the sink. The flow path linking each source to its sink serves to trace the control volume within which the flow is routed. The response function is defined for each flow path, which describes the shape of the hydrograph at the sink given an instantaneous input at the source. The response function includes a measure of the travel time and the losses due to evaporation and infiltration along the flow path. No additional flow is allowed to enter the flow path between the source and the sink since a separate source is defined for each geographic location. Even though in reality flow from various sources may be entering the same channel. The term translational velocity is synonymous to the wave celerity and is used to differentiate it from flow velocity at a given cross section. If different velocity zones exist, their combined effect along a flow path can be determined by expressing velocity in terms of flow time through each segment and adding up to get the total flow time for the entire reach. Velocities along a flow path cannot be averaged without accounting for the direction and magnitude in each direction because velocity is a vector quantity. On the other hand flow time is a scalar quantity and can be summed without taking into account the direction (Asante[7]).

The storage effects that describe the deformation of the input should also be accounted for. The storage effect is attributed to the shear forces between the sides of the channel and the moving water. These forces result in a velocity profile such that the particles closer to the channel are transported at a slower velocity than the particles near the center of the channel (Dr. Chiu's lecture). This results in a longitudinal spreading of the input water as it travels downstream. The damping effect of the irregular channel sections also spreads the input.

These irregularities result in the storage of water along the banks of the channel thus delaying of the input water at a downstream location. Linear reservoirs describe the storage effects between two interconnected elements so it cannot be used to explain the storage effects in the source to sink model because the source and the sink are not connected to each other. The only alternative is to use the Lag and Route method. But they explain the dispersion only approximately. Therefore the best method to use would be something that is derived from the St. Venant's equations since they incorporate the full description of the dispersion process.

3.2 GIS

GIS (Geographical Information System) may be defined as an application specific or generic software package that allows users to capture, edit, and display geographical data as well as perform analysis and create thematic maps. It is supported by a variety of different components such as data base management, decision statistical system, image analysis, overlaying of different map layers ,etc.

3.2.1 Raster Data Type

The grid data structure is a discrete representation of the terrain based on square cells arranged in rows and columns. Grids are used to describe spatially distributed terrain parameters like elevation, land use, soil type, etc. and one grid is necessary for each parameter that is to be represented. These numeric grid cell values are used not only for analysis but also for display. By assigning a specific color in a palette to designated numeric ranges, a very fine matrix like color image is formed. The density of the grid cells should be large enough to resemble the continuous character of the terrain. Raster layers are both simple in structure and regular in their organization, allowing an extraordinary range of analytical operations.

While the logical structure of an image file is a grid, the actual structure, as it is stored, is a single column of numbers. For instance, an image consisting of 3 rows and 4 columns is stored as a single column of 12 numbers. The image that looks like

10	15	19	10
1	14	10	11
14	3	11	10

Has an image file that looks like this in the internal representation:

10
15
19
10
1
14
10
11
14
3
11
10

The raster documentation file, containing the number of rows and columns, allows the image to be correctly recreated for display and analysis.

IDRISI has five sub data types of raster images which are differentiated on the basis of the data types that are used to represent cell values. They are integer, byte, real, GB8 and RGB24. The data types that were used in this study are described below.

3.2.1.1 Integer. Integers are numbers that have no fractional part and lie within the range of –32768 to +32767. Integer files are sometimes called 16-bit integer files since they require 16 bits (or 2 bytes) of memory per value (and therefore per pixel). Integer values can be used to represent quantitative values or can be used as codes for categorical data types. For example: a soil map may record three soil types in a particular region. Since IDRISI images are stored in numeric format these types can be given integer codes 1, 2 and 3. The documentation file records the legend for these, on the relationship between the integer codes and the actual soil type.

3.2.1.2 Real. Real numbers have a fractional part such as 3.14. Real numbers are used whenever a continuous data variable is being used with great precision or whenever the data range exceeds that of the integer type. The real numbers can store a value between the range +-1x10E38 with a precision of 7 significant figures. Each number and therefore each digit takes 4 bytes of storage space.

3.2.2 Vector Data Type

All vector files describe one or more distinct features. Unlike raster images that describe the totality of space within a rectangular area vector files may describe only a small number of features within a similarly defined rectangular region. Each feature is described by means of a single numeric attribute value and one or more X,Y coordinate pairs that describe the location, course or boundary of that feature. These points will be joined by a straight line segments when drawn. Thus, curved features require a great number of closely spaced points to give the appearance of smooth curves. The numeric attribute values can represent either identifiers or actual numeric data values and can be stored either as an integer or a real number. The different types of vector files can be point, line and polygon.

3.2.2.1 Point Files. These files are used to represent features for which only the location is of importance. For example the location of the rain gauges in a watershed or fire hydrants in the city. Each point feature is described with an attribute value that can be integer or real and an X,Y coordinate pair.

3.2.2.2 Line Files. These files describe features like streams, rail-roads and streets. Each line feature in a layer is described by an attribute value that can be integer or real, a count of the number of points that make up the line and a series of X,Y coordinate pairs for each point.

3.2.2.3 Polygon Files. These files describe the areal features such as soil types, forest stands, residential areas, etc. Each polygon feature in a polygon layer is described by an attribute value that can be an integer or a real number, a count of the number of parts in the polygon, and for each part, a list of the points that make up that part. The points are then described using the X,Y coordinate points. The parts of a polygon are concerned with the issue of holes. A polygon with one part will have no holes and a polygon with two parts will have a single hole and so on.

3.3 Time-Area Method

The basis of the time area method is the development of the time area histogram. The time area histogram is the plot of the time of travel and the portion of the watershed (henceforth referred as sub area) that is having that particular time of travel. The time of travel of the rainfall occurring in any location (source) of the sub area of the watershed will be the same for all the locations in the same sub area of the watershed. The cumulative time of travel for all the locations of the watershed is computed and then the watershed is divided into sub areas of equal time of travel by isochrones. Thus isochrones may be defined as the contours, which connect all the locations having the same time of travel. The isochrones cannot cross each other, cannot enclose each other and must begin and terminate at the watershed boundaries (Dooge, 1959)[31]. The time area may be used in the lag and route method in which the excess rainfall is lagged by the amount of the time interval of the isochrones that divide the watershed into zones of equal intervals of the time of travel. However it is to be noted that the time area method only accounts for the translational transformation of the inflow and that the storage effects of the watershed are left unconsidered. Not considering the storage effects leads to the lack of attenuation in the hydrograph, which would then show a higher peak of discharge. This storage effect can be accounted for by routing the hydrograph developed from the time area histogram through a linear reservoir with an appropriate storage coefficient that properly approximates the watershed characteristics.

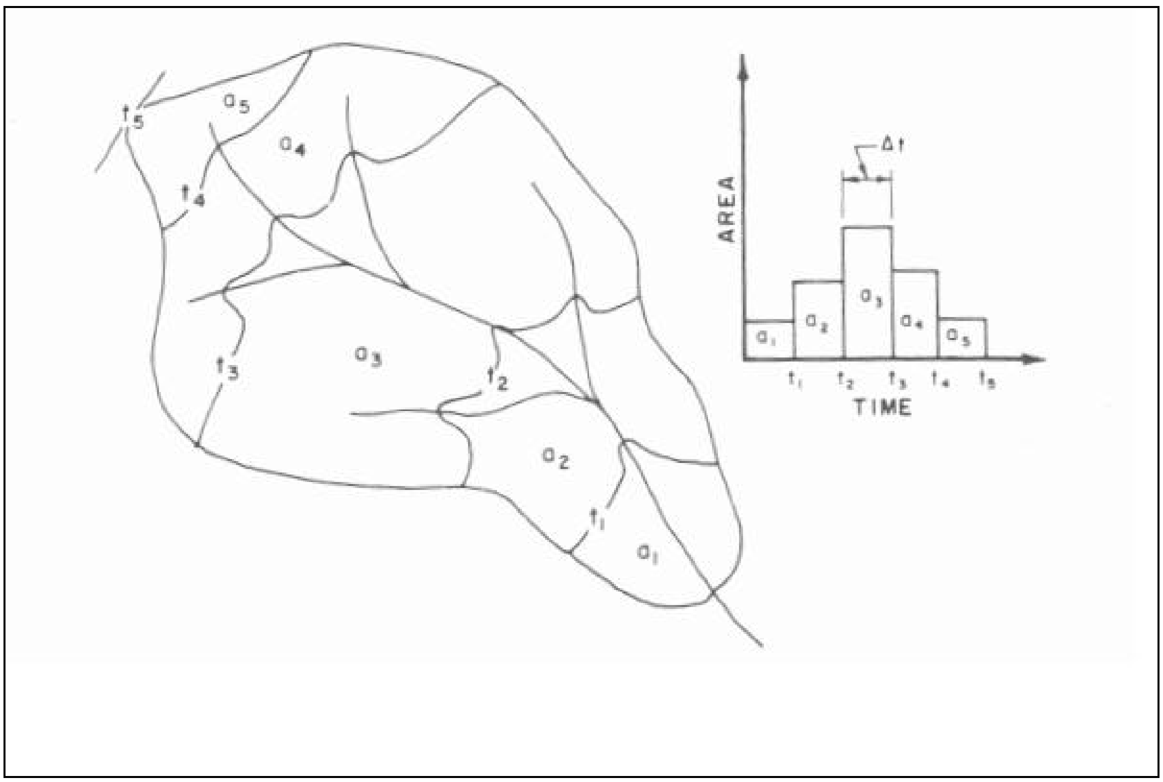

Figure 3-1 Watershed showing Isochrones and Time-Area diagram

CHAPTER 4

4.0 DATA COLLECTION

To make the maximum possible use of the GIS facilities available at hand the data should be in the digital form. The digital data can be in form of raster files or the vector files. Having the data in digital form makes it easier to process using a computer. For the research at hand, three data files are required, the DEM of the quadrangle containing the watershed, the land-use land-cover data file and the soil type data file. If the land use or the soil data is available in form of paper maps then they need to be digitized, to be used in the research.

4.1 Digital Elevation Model

The Digital Elevation Model (DEM) is the very basic data that is required to start processing a watershed. A Digital Elevation Model can be defined as a database or a file that contains the elevation data in digital form that describes the geographical surface of an area. It consists of an array of uniformly spaced elevation data. The elevation data or the DEM is point based but can easily be converted to raster format by placing the elevation at the center of the cell. DEMs are available in a number of resolutions depending upon the amount of area they cover. The United States Geological Survey (USGS) classifies them into 4 types namely, 7.5 minute, 30 minute, 1 degree and Alaska DEM.

The 7.5 minute has a 10 to 30 meter data spacing in the UTM (Universal Transverse Mercator) projection and it covers 7.5 x 7.5 minute square block that corresponds to the USGS 1:24000 scale quadrangle. That the 7.5 minute DEM has a resolution of 30 meter grid means that it records the elevation data at the intersection of 30 meter grids. According to USGS the vertical accuracy of these DEMs is up to 15 meters. The 30 minute DEM has a data spacing of 2 arc seconds (approximately 60 meters in mid latitudes). This corresponds to east or west half of USGS 30 x 60 meter in 1:100000 scale quadrangle. The vertical accuracy in these is up to 25 meters. The 1 degree DEM has a data spacing of 3 arc seconds (approximately 100 meters in mid latitudes). It covers a 1 x 1 degree block corresponding to east or west half of a USGS 1 x 2 degree (1:250000 scale quadrangle). The vertical accuracy in these is up to 30m meters. The Alaska DEM are different in the sense that they are rectangular in shape. The 7.5 minute Alaska DEM have 1 arc second latitude x 2 arc second longitude, while the 15 minute Alaska DEM have 2 arc second latitude x 3 arc second longitude.

For this study a 7.5 minute DEM with 30m spacing grid is used. The DEM can either be obtained from the USGS (United States Geological Survey) or some other commercial data providers. From the USGS the DEM can either be downloaded from

http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html

or the DEMs can be ordered on CD from

Earth Science Information Center State Offices and State Representatives

Pennsylvania

Department of Conservation and Natural Resources

Pennsylvania Geological Survey

P.O. Box 8453

Harrisburg, PA 17105-8453

Telephone: 717-783-8077

Fax: 717-783-7267

The topographical maps can be ordered from

USGS Map Dealers for Pennsylvania

HUCH'S SPORT SHOP

9012 PERRY HWY

PITTSBURGH, PA 15237

(412) 364-5006

J R WELDIN CO

415 WOOD ST

PITTSBURGH, PA 15222

(412) 281-0123

PEN OH WES MAP CO

TIME BUILDING

336 4TH AVE

PITTSBURGH, PA 15222

(412) 261-0645

SHAW WEIL ASSOCIATES

5131 PENTON ROAD

PITTSBURG, PA 15213

(412) 495-4264

4.2 Soil Data

The soil type and the land use data in digital form for the area of interest can be ordered from the USGS or can be downloaded from the Pennsylvania Spatial Data Access web site.

http://www.pasda.psu.edu

The data can also be ordered on map sheets from the USDA (United States Department of Agriculture) . The map sheets can then be digitized into a vector file to be used with the available software.

4.3 Land Use Data

The soil type and the land use data in digital form for the area of interest can be ordered from the USGS or can be downloaded from the Pennsylvania Spatial Data Access web site.

http://www.pasda.psu.edu

The data can also be ordered on map sheets from the USDA (United States Department of Agriculture) . The map sheets can then be digitized into a vector file to be used with the available software.

The University of Pittsburgh library also has a lot of data for the different counties of the state of Pennsylvania.

CHAPTER 5

5.0 DATA PROCESSING AND COMPUTER METHODS

The DEM obtained needs a lot of processing and the complexity of the processes involved, solicit the use of a GIS which has several analytical tools.

5.1 Geographic Information System

GIS (Geographic Information Systems) may be defined as an application specific or generic software package that allows users to capture, edit, and display geographical data as well as perform analysis and create thematic maps. It is supported by a variety of different components such as decision statistical system, image analysis, overlaying of different map layers, etc.

A GIS is an analytical tool. The major advantage of a GIS is that it allows one to identify the spatial relationships between map features. GIS links spatial data with geographical information about a particular feature on a map. This information is stored as attributes of a graphically represented feature. GIS uses these attributes to compute new information about map features.

For this research the GIS software used is IDRISI. It has been developed by the Graduate School of Geography at the Clark University. The processing of the DEM involves the following steps.

5.2 Processing the DEM

The DEM needs to be processed to create the elevation file, the flow direction file, the watershed file and the stream network file. These files are required as inputs for the Fortran program for generating the time area histogram. Following are the steps that would create the files. These steps have been outlined for the Thompson Run watershed. The figures and names of the files in italics are the inputs that the user needs to feed in to the computer to get the modules and the programs to function. The paths of the inbuilt modules of IDRISI are also given in italics.

5.2.1 Importing the DEM into IDRISI

The very first step is to define a Data Path, which simply means telling the software about the folder from which and to which it should receive and send the files. The Thompson Run watershed is located in the Braddock quadrangle. Create a folder called *braddock* in the C: drive and copy the braddock.dem file (procured from the USGS) in this folder. Now all the files that are created are going to be stored in the folder *braddock*. Then the DEM can be imported into IDRISI using the DEMIDRIS module.

(*File* --> *Import* --> *Government Agency Data Formats* --> *DEMIDRIS*)

Choose *braddock* as the input DEM file and put *brad* as the output IDRISI image. This creates the output raster file brad.rst, and also a documentation file brad.rdc. The file so produced will have the Data Type as integer and File type as binary (this information is contained in the Metadata file), if the data type isn't integer then it can be converted into one using the CONVERT module. This is a very important requirement so one should make sure that all the raster files being generated are of Data Type integer and File Type binary. (*Reformat* --> *CONVERT*)

5.2.2 Filling the Single Cell Depressions

After importing the DEM into IDRISI, we need to process the resulting raster file. The very first step is to remove the pits or the single cell depressions that are present in the raster file. These single cell depressions are usually the result of the process of creating the DEM and need to be filled to obtain a topology that is free of erroneous depressions. This can be done using the PIT REMOVAL module of IDRISI.

(*Analysis* --> *Surface Analysis* --> *Feature Extraction* --> *PIT REMOVAL*)

Input DEM file as *brad.rst* and name the output file as *b_pit-removed.rst.*

. The single cell depression filling can also be done using the Fortran program FILLSNGL (Michelini)[21]. It takes the following inputs.

1) Length and width of the elevation file (number of rows and columns).

   (*Enter: 468 359*)

2) Name of the elevation file which one wants to give to the corrected elevation file.

   (Enter: brad.rst)

The FILLSNGL program updates the raster file created in the DEMIDRIS module. In this study the PIT REMOVAL module was used so the subsequent processing would use the raster file *b_pit-removed.rst.*

5.2.3 Generating the Flow Direction File

After the pits have been removed the Fortran Program DIRECT is executed which determines the flow directions by calculating the slopes between adjacent cells with flow occurring along the direction of the steepest slope. The DIRECT program takes the following inputs.

1) Length and width of the elevation file (number of rows and columns).

   (Enter: 468 359)

2) Name of the elevation file.

   (Enter: b_pit-removed.rst)

4) Name of the flow direction file.

   (Enter: b_direction.rst)

If prompted with a message "File Unit # missing" enter *b_direction* without the .rst extention. This creates the flow direction raster file, but the document file needs to be created. This can be done using the METADATA module

(File->Metadata)

Create the metadata file for raster using the parameters from the b_pit-removed.rdc file and name it *b_direction.rdc*.

5.2.4 Developing the Stream Network

The next step is to generate the stream network in the quadrangle. This is accomplished by the RUN OFF module.

(*Analysis --> Surface Analysis --> Feature Extraction --> RUN OFF)*

Input surface image as *b_pit-removed.rst* and the output file as *b_stream_network.rst*.

This b_stream_network.rst file so generated has Data Type as real. One can generate the stream network using a smallest contributing area by specifying the number of cells that must contribute to the runoff to generate the stream flow. This user specified number of contributing cells can be done using the RECLASS module.

(Analysis --> Data Query --> RECLASS)

In the RESAMPLE dialog box input file as *b_stream_network* and output file as *b_stream100*, suppose we need to make the minimum number of contributing cells as 100, assign a new value 0 to all values from 0 to just less than 100 and assign a new value of 1 to all values from 100 to just less than 37000 (the maximum value that the integer values can take). The file b_stream100 is of Data Type byte and hence it needs to be converted to Data Type integer using the CONVERT module. The resulting raster file is of Data Type integer and File Type binary and can be used in the subsequent processing.

5.2.5 Delineating the Watershed and Sub watersheds

To generate the watersheds or sub-watersheds, the Fortran program WTRSHED is used. It takes the following inputs.

1) Length and Width of the raster file with pits removed.

(Enter: 468 359)

2) The Direction raster file generated from the execution of the DIRECT program.

(Enter: b_direction.rst)

3) The name of the watershed mask file.

(Enter: b_ws__big.rst)

The watershed mask file can be created as follows:

1) Create a blank raster file with an initial value of –1 using the INITIAL module.

(Data Entry --> *INITIAL)*

Click the radio button “copy spatial parameters from another image”. Enter the output image as *b_ws_big* (the name of the mask file), and copy parameters from *b_pit-removed* choose the file type as integer and the initial value as –1.

2) Using the UPDATE *(Data Entry* --> *UPDATE)* module update the above file with the number (value=1) to be given to the watershed and the row (both first and last same) and column (both first and last same) numbers of the outlet of the watershed (these can be looked up in the stream file *b_stream100.rst*).

If sub watersheds are to be generated then in the UPDATE module dialog box the values for the sub watersheds and their corresponding row and columns numbers need to be input. The values for generating the sub watersheds of Thompson Run can be looked up in Table 6-1.

5.2.6 Changing the Resolution of Raster File

One of the objectives of this research is to investigate the effect of grid size or resolution of the DEM on the surface runoff and the resulting hydrograph. For this, the grid size of the initial DEM which was 30 meters was changed into integer multiples and factors of the initial resolution. IDRISI has two modules that would do this for us. The files so generated would be like brad, the very first file that one needs to do the rest of the processing.

5.2.6.1 Reducing the Resolution. Decreasing the resolution, that is, creating a raster file with 60 meter or 90 meter resolution can be accomplished by the CONTRACT module using the contraction factor of 2 or 3 for both X and Y directions.

(Reformat --> CONTRACT)

Enter the input file as *brad* and the output file as *b_ c2.rst* choose 2 for both the contraction factors and choose the radio button pixel aggregation.

5.2.6.2 Increasing the Resolution. Increasing the resolution that is creating a raster file with 15 meter or 10 meter resolution can be accomplished by the EXPAND module using the contraction factor of 2 or 3 for both X and Y directions.

(Reformat --> EXPAND)

Note: One needs to pay attention to the contraction type.

By thinning, the alternate cells are not taken into consideration while computing the elevation values at the new resolution. By aggregation, the resulting cells would contain the average of the adjacent cells.

(This makes more sense and hence has been employed in this study. However the average values would result in a Data Type real and this needs to be converted into Data Type integer using the CONVERT module.)

5.3 Developing the Soil Raster File

The soil data that was obtained from the USGS site was in ARC/INFO format. Another GIS software ARCVIEW was employed to do the initial processing to get the shape file which could then be imported into IDRISI. The data at hand is for the whole Allegheny County so one needs to clip the required area of the watershed from that shape file using the Geo-Processing Wizard of ARCVIEW. The resulting shape file (thompson_soil.shp) was then re-classed according to Table 5-1 shown on the next page which puts the different soil types into one of the Hydrologic Soil Groups (A,B,C or D).

Once the required shape is generated in Arc-View, it is imported into IDRISI using the SHAPEIDR module.

(Import --> *Software-Specific Formats* --> *SHAPEIDR)*

Input the shape file *thompson_soil.shp*, enter the output vector file as *th_soil.vct,* the reference system as *us27tm17.ref* , and units as meters.

It creates a vector file *th_soil.vct*. Since the projection of the imported shape file was unknown, to change it's projection to UTM, RESAMPLE module was used.

(Reformat --> *RESAMPLE)*

Resample basically means getting a relation between the original projection and the new one that we want to project into. It involves creating a correspondence file, which means identifying several points in the watershed in both the old and the new projection and enlisting the coordinates. The correspondence file for Nine Mile Run watershed is given in Figure 5-1 and for Thompson Run watershed in Figure 5-2. The correspondence file can be created using the editor *(Data Entry* -> *Edit).* The first value is the number of coordinates that the correspondence file has, and the coordinates are arranged as old x-coordinates, old y-coordinates, new x-coordinates and new y-coordinates. Enter these values in the editor and save the file as a correspondence file *(thompson.cor)*.

In the RESAMPLE dialog box choose the type of file as vector, enter the input file as *th_soil.vct* and the output file as *th_soil_res.vct,* enter the correspondence file as *thompson.cor* and choose the mapping function as quadratic. Click on the "output refence parameters" button and input the parameters from the b_pit-removed.rdc metadata file. This resampled vector file in UTM projection *(th_soil_res.vct),* is used to create a raster soil file using the POLYRAS module. *(Reformat* --> *Raster/Vector Conversion* --> *POLYRAS)*

Table 5-1 Soil Types and their Hydrologic Soil Groups

state	soil code	name of the soil	soil group
PA	AgB	Allegheny silt loam, coarse subsoil Variant, 2 to 8 percent slopes	B
PA	AgC	Allegheny silt loam, coarse subsoil Variant, 8 to 15 percent slopes	C
PA	At	Atkins silt loam	A
PA	BrB	Brinkerton silt loam, 2 to 8 percent slopes	B
PA	CaB	Cavode silt loam, 2 to 8 percent slopes	B
PA	CaC	Cavode silt loam, 8 to 15 percent slopes	C
PA	CkB	Clarksburg silt loam, 3 to 8 percent slopes	B
PA	CkC	Clarksburg silt loam, 8 to 15 percent slopes	C
PA	CmB	Clymer silt loam, 3 to 8 percent slopes	B
PA	CmC	Clymer silt loam, 8 to 15 percent slopes	C
PA	CmD	Clymer silt loam, 15 to 25 percent slopes	D
PA	CuB	Culleoka silt loam, 3 to 8 percent slopes	B
PA	CuC	Culleoka silt loam, 8 to 15 percent slopes	C
PA	CuD	Culleoka silt loam, 15 to 25 percent slopes	D
PA	CwB	Culleoka-Weikert shaly silt loams, 3 to 8 percent slopes	B
PA	CwC	Culleoka-Weikert shaly silt loams, 8 to 15 percent slopes	C
PA	CwD	Culleoka-Weikert shaly silt loams, 15 to 25 percent slopes	D
PA	DoB	Dormont silt loam, 2 to 8 percent slopes	B
PA	DoC	Dormont silt loam, 8 to 15 percent slopes	C
PA	DoD	Dormont silt loam, 15 to 25 percent slopes	D
PA	DoE	Dormont silt loam, 25 to 35 percent slopes	A
PA	Du	Dumps, coal wastes	A
PA	Dw	Dumps, industrial wastes	A
PA	ErB	Ernest silt loam, 2 to 8 percent slopes	B
PA	ErC	Ernest silt loam, 8 to 15 percent slopes	C
PA	ErD	Ernest silt loam, 15 to 25 percent slopes	D
PA	EvB	Ernest-Vandergrift silt loams, 3 to 8 percent slopes	B
PA	EvC	Ernest-Vandergrift silt loams, 8 to 15 percent slopes	C
PA	EvD	Ernest-Vandergrift silt loams, 15 to 25 percent slopes	D
PA	GP	Gravel Pits	A
PA	GQF	Gilpin-Upshur complex, very steep	A
PA	GSF	Gilpin, Weikert, and Culleoka shaly silt loams, very steep	A
PA	GlB	Gilpin silt loam, 2 to 8 percent slopes	B
PA	GlC	Gilpin silt loam, 8 to 15 percent slopes	C
PA	GlD	Gilpin silt loam, 15 to 25 percent slopes	D
PA	GpB	Gilpin-Upshur complex, 3 to 8 percent slopes	B
PA	GpC	Gilpin-Upshur complex, 8 to 15 percent slopes	C
PA	GpD	Gilpin-Upshur complex, 15 to 25 percent slopes	D
PA	GrE	Gilpin-Vandergrift silt loams, slumped, 15 to 35 percen t slopes	A
PA	GuB	Guernsey silt loam, 2 to 8 percent slopes	B
PA	GuC	Guernsey silt loam, 8 to 15 percent slopes	C
PA	GuD	Guernsey silt loam, 15 to 25 percent slopes	D
PA	GvB	Guernsey-Vandergrift silt loams, 3 to 8 percent slopes	B
PA	GvC	Guernsey-Vandergrift silt loams, 8 to 15 percent slopes	C
PA	GvD	Guernsey-Vandergrift silt loams, 15 to 25 percent slopes	D
PA	Gx	Gullied Land	A
PA	HTE	Hazleton loam, steep	A
PA	HaB	Hazleton loam, 3 to 8 percent slopes	B
PA	HaC	Hazleton loam, 8 to 15 percent slopes	C
PA	HaD	Hazleton loam, 15 to 25 percent slopes	D
PA	Hu	Huntington silt loam	A
PA	LbB	Library silty clay loam, 3 to 8 percent slopes	B
PA	LbC	Library silty clay loam, 8 to 15 percent slopes	C
PA	LbD	Library silty clay loam, 15 to 25 percent slopes	D
PA	Ln	Lindside silt loam	A
PA	Ne	Newark silt loam	A
PA	Ph	Philo silt loam	A
PA	QU	Quarries	A
PA	RaA	Rainsboro silt loam, 0 to 3 percent slopes	A
PA	RaB	Rainsboro silt loam, 3 to 8 percent slopes	B
PA	RaC	Rainsboro silt loam, 8 to 15 percent slopes	C
PA	RyB	Rayne silt loam, 2 to 8 percent slopes	B
PA	RyC	Rayne silt loam, 8 to 15 percent slopes	C
PA	SmB	Strip Mines, 0 to 8 percent slopes	C
PA	SmD	Strip Mines, 8 to 25 percent slopes	D
PA	SmF	Strip Mines, 25 to 75 percent slopes	A
PA	UB	Urban Land	A
PA	UCB	Urban Land-Culleoka complex, gently sloping	B
PA	UCD	Urban Land-Culleoka complex, moderately steep	D

Create a new empty raster file using INITIAL module, name the output file as *th_soil_ras.rst*, copy the parameters from *b_pit-removed.rst* file, make the data type as integer and the initial value as 0. In the POLYRAS dialog box, enter the vector polygon file as *th_soil_res.vct* and the file to be updated as *th_soil_ras.rst*.

This raster file along with the raster file for the land use (th_land_ras.rst) is used in the curve number generation program.

```
11
420402.913659 125293.839419 596070.019271 4477247.056140
420466.317167 124417.535838 596250.200521 4476406.166314
420276.106642 123403.979889 595979.928646 4475415.117585
417771.668064 123129.475153 593517.451562 4475024.704449
415753.323050 123182.264526 591505.427604 4475054.736229
415890.697318 125452.207536 591595.518229 4477217.024364
416524.732401 126127.911502 592346.273438 4478148.009534
419515.264542 126138.469377 595229.173438 4478178.041314
420550.855178 127257.604070 596100.049479 4479109.026483
421153.188507 126254.605996 596820.774479 4478298.168432
421206.024764 125726.712273 596680.824896 4477757.596398
```

Figure 5-1 Correspondence file for Nine Mile Run

5.4 Developing the Land Use Raster File

The land use data file can also be processed in exactly the same way as the soil data to create the land use raster file (th_land_ras.rst). This is used along with the soil raster file to get the curve numbers for the watershed and also generate the curve number raster file for that watershed.

```
40
424597.551289 129983.460370 600084.452867 4482157.228284
425288.418124 129810.620684 600079.772972 4481978.658369
426152.001668 129522.554541 606129.979653 4481740.565148
426842.868503 128811.991839 602373.021377 4481026.285487
427361.018630 129253.692808 602878.289749 4481442.948623
428646.798573 128888.809027 604186.043183 4481175.093750
429222.520936 128101.428236 604810.198231 4480431.052436
430335.584170 128178.245874 605969.343321 4480579.860699
429606.335844 126505.075474 605285.744935 4478913.208157
429990.150753 126084.965235 605612.683293 4478556.068326
429376.046899 124836.678616 605107.414921 4477276.317267
427821.596520 124836.678616 603532.166466 4477067.985699
426996.394467 123242.712656 602729.681405 4475490.618114
426305.527631 122839.420025 602046.083019 4474954.908359
425710.614523 122916.237663 601481.371308 4475133.478284
424942.984706 122512.945022 600708.607160 4474627.530191
424520.788307 121322.271677 600322.226219 4473437.064089
424194.545635 121456.702539 600114.174536 4473585.872352
423599.632527 121015.001120 599608.906164 4473050.162606
423522.869545 123473.165539 599281.967806 4475550.141419
423733.967745 123569.187587 599460.297819 4475788.234640
423465.297309 124279.750740 599192.802799 4476323.944386
422985.528673 124529.408064 598717.256095 4476591.799258
422179.517365 125720.081454 597885.049365 4477722.742055
421277.552331 125758.490273 596874.512620 4477782.265360
421162.407858 126238.600512 596815.069282 4478258.451801
421296.743076 126910.754845 596933.955928 4478913.208157
421028.072640 127102.798940 596666.460938 4479121.539723
420740.211459 127275.638626 596309.800910 4479270.347987
420989.691149 127640.522407 596547.574262 4479627.487818
421277.552331 127506.091514 596904.232489 4479538.202860
421566.413512 127870.975322 597082.564303 4479865.581038
422121.945129 127333.251855 597706.719351 4479359.632945
422620.904510 127275.638629 598182.266054 4479329.871289
422736.048903 127774.953274 598330.874399 4479865.581039
423254.199109 128101.428236 598865.864400 4480163.197564
423618.823272 127621.317998 599163.081130 4479776.296081
424520.788307 128504.720836 600025.009530 4480639.384004
424156.164144 129176.875170 599668.349502 4481383.425318
424482.406816 129618.576589 599995.287861 4481770.326801
```

Figure 5-2 Correspondence file for Thompson Run

5.5 Generating the Precipitation File

In the absence of real time rainfall data, for simulation purposes the rainfall distribution file was created in form of raster file. The precipitation file is created using the Fortran program PREC_REAL_KNK. The program requires a mask file similar to that used in the delineation of the watershed. To create a mask file, make a new raster file using the INITIAL module, copy parameters from *b_pit-removed.rst* and name the raster file as *th_prec.rst*. Make the type of file as real and the initial value as –1.0. This raster file is then updated with the values of the precipitation that one wants (1.0,1.25,1.5,1.75 and 2.0), using the UPDATE module and the rows and columns from Table 6-1.

The PREC_REAL_KNK Fortran program takes the following inputs.

1) Length and width of file.

(Enter: 468 359)

2) Name of the flow direction file.

(Enter: b_direction.rst)

3) Name of the mask file.

(Enter: th_prec.rst)

The file th_prec.rst is the precipitation file to be used in the analysis.

5.6 Generating the Curve Numbers file

The Curve Number raster file for the watershed is generated using the soil raster file and the land raster file generated before. The Fortran program CURVE_NUMBER_KNK is used to create the Curve Number raster file, it takes the following inputs.

1) Length and width of the file.

(Enter: 468 359)

2) Name of the watershed file.

(Enter: b_ws_big.rst)

3) Number of the watershed.

(Enter: 1)

4) Name of the soil raster file.

(Enter: th_soil_ras.rst)

5) Name of the land use raster file.

(Enter: th_land_ras.rst)

6) Name of the curve number file.

(Enter: th_curve-number.rst)

5.7 Analysis and Isochrones generation

The files generated until now are needed for the execution of the Fortran program that does all the analysis, creating several files which give the ordinates of the time area curve, the amount of runoff being generated and also generates the isochrones file for the watershed. The Fortran program MOD_TA&EX_V+SCS takes the following inputs.

1) Length(rows) and width(columns) in the elevation file.

(Enter: 468 359)

2) Name of the elevation file corrected for the single cell depressions.

(Enter: b_pit-removed.rst)

3) Name of the watershed file.

(Enter: b_ws_big.rst)

4) Name of the stream network file.

(Enter: b_stream100.rst)

5) Name of the flow direction file.

(Enter: b_direction.rst)

6) Name of the isochrones file.

(Enter: th_iso_10min.rst)

7) Name of the precipitation file.

(Enter: th_prec.rst)

8) Name of the curve numbers raster file.

(Enter: th_curve-number.rst)

9) The grid size of the Digital Elevation Model.

(Enter: 30)

10) The number of the watershed to be analyzed.

(Enter: 1)

11) The average value of the curve number of the watershed for developing the isochrones. This is obtained from the text file created by the Fortran program CURVE_NUMBER_KNK.

(Enter: 78)

12) The time interval for the time area diagram in minutes.

(Enter: 10)

The Fortran program MOD_TA&EX_V+SCS is used when one is working with the distributed curve numbers (that is using the Curve Number raster file). If one needs to work with only a single Curve Number for the whole watershed, one should use the program MOD_TA&EX_V+SCS_CONST_CN. Both these programs create four files namely the data file, the time area file, the runoff file and the record file.

5.8 Generating the Hydrograph

The runoff file (EX_PREC.TXT) generated by the analysis program above is used to generate the hydrograph file. The Fortran program MUS_HYDRO_EXPREC_KNK does it using the following inputs.

1) The storage factor in minutes, either the time of concentration or some other value.

(Enter: 30)

2) The wedge factor

(Enter: 0)

3) Initial discharge

(Enter: 0)

4) Grid size in the analysis

(Enter: 30)

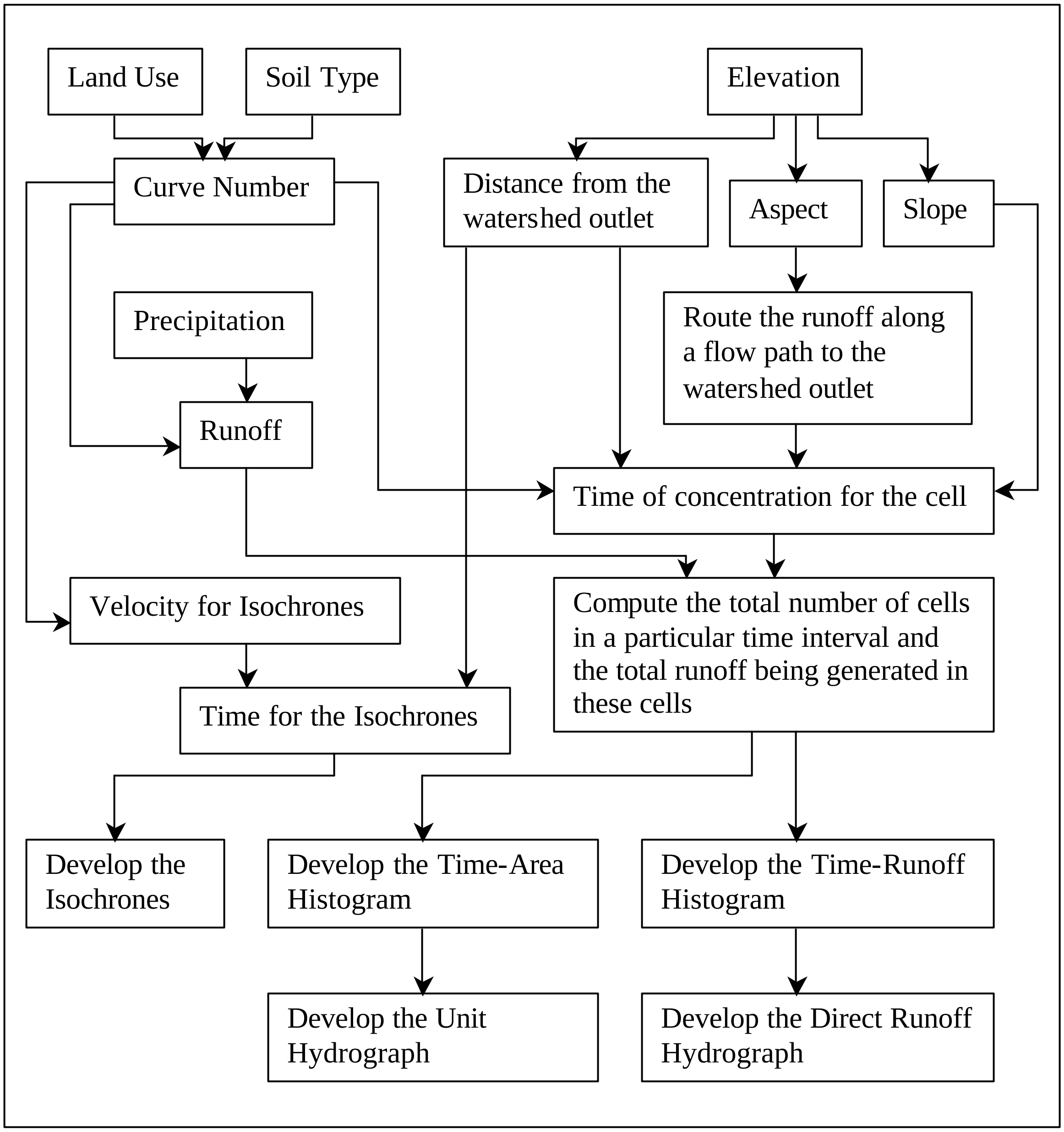

Figure 5-3 Source-to-Sink Model Flow-chart

CHAPTER 6

6.0 CASE STUDY

6.1 Watersheds

The watersheds used for this study were chosen based on their shape and their size so that the developed model could be tested on the spatial extent of the watersheds under study. Since the evaluation of the model was not part of the study it was not necessary for the watersheds to have rain gauges or stream gages to measure the rainfall and the stream flow. The two watersheds chosen were the Thompson Run and the Nine Mile Run in the Pittsburgh area. The Thompson Run watershed has a leaf-like shape of a typical watershed with an area of 15.8 square miles. The Thompson Run has predominantly group D soil (43%), which is heavy clay and some saline soils, which have a high runoff potential. The distribution of the soil types in the Thompson Run watershed is given in Figure 6-5. The land use in the watershed is 28 % forested and 50% residential. The land use distribution is given in Figure 6-7.

The Nine Mile Run has an area of 6.2 square miles. The soil type is mainly sandy loam and shallow loess i.e. group B soil (40%). For the soil type distribution, refer to Figure 6-6. The land use in this watershed is mostly residential (40%). For land use distribution refer Figure 6-8.

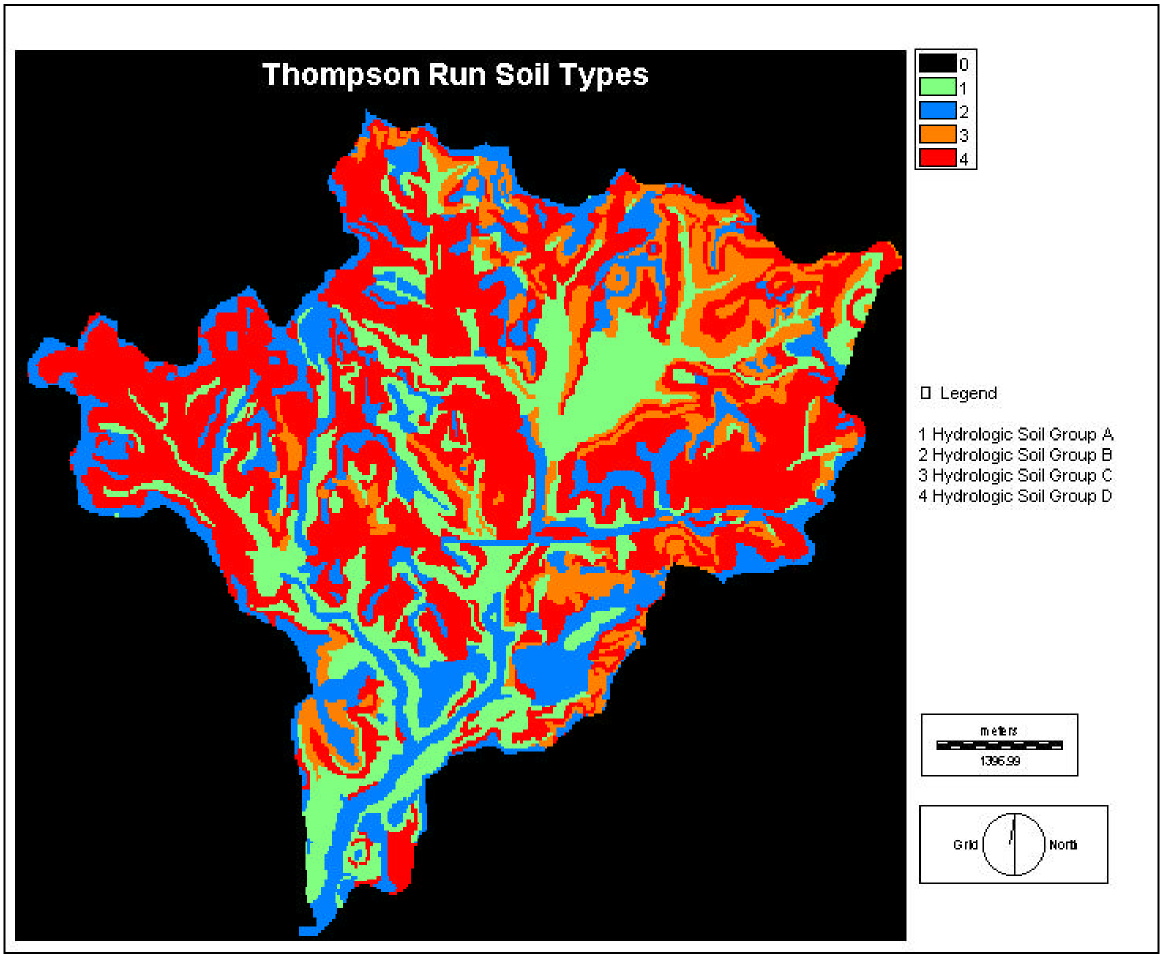

Figure 6-1 Soil types for Thompson Run Watershed

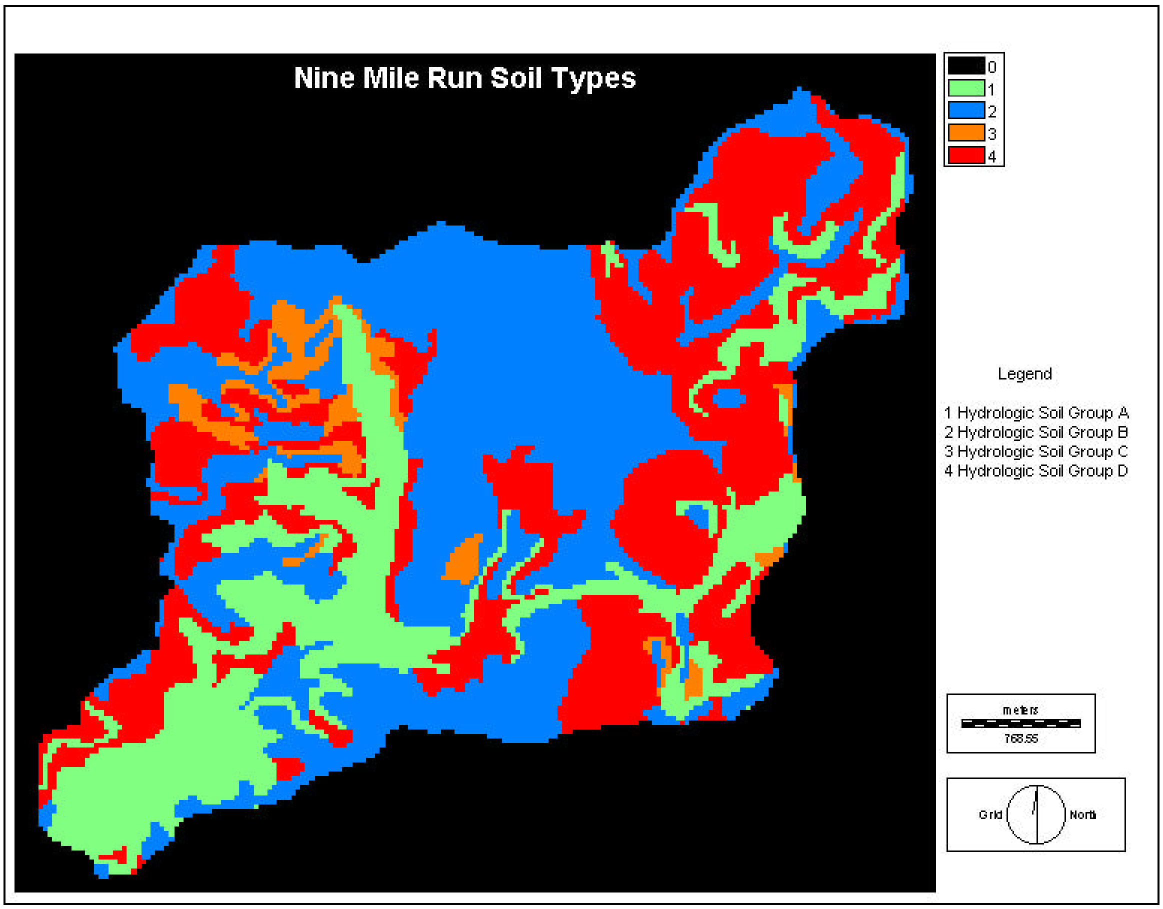

Figure 6-2 Soil types for Nine Mile Run Watershed

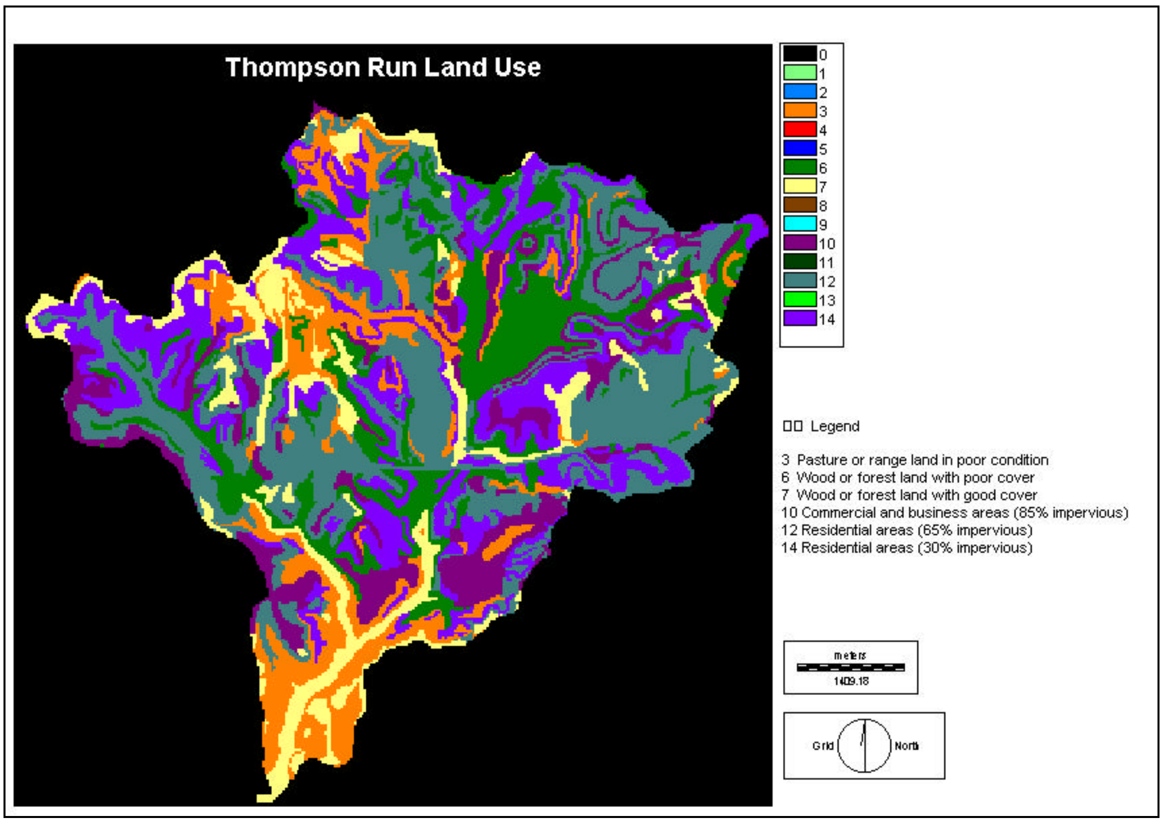

Figure 6-3 Land Use for Thompson Run Watershed

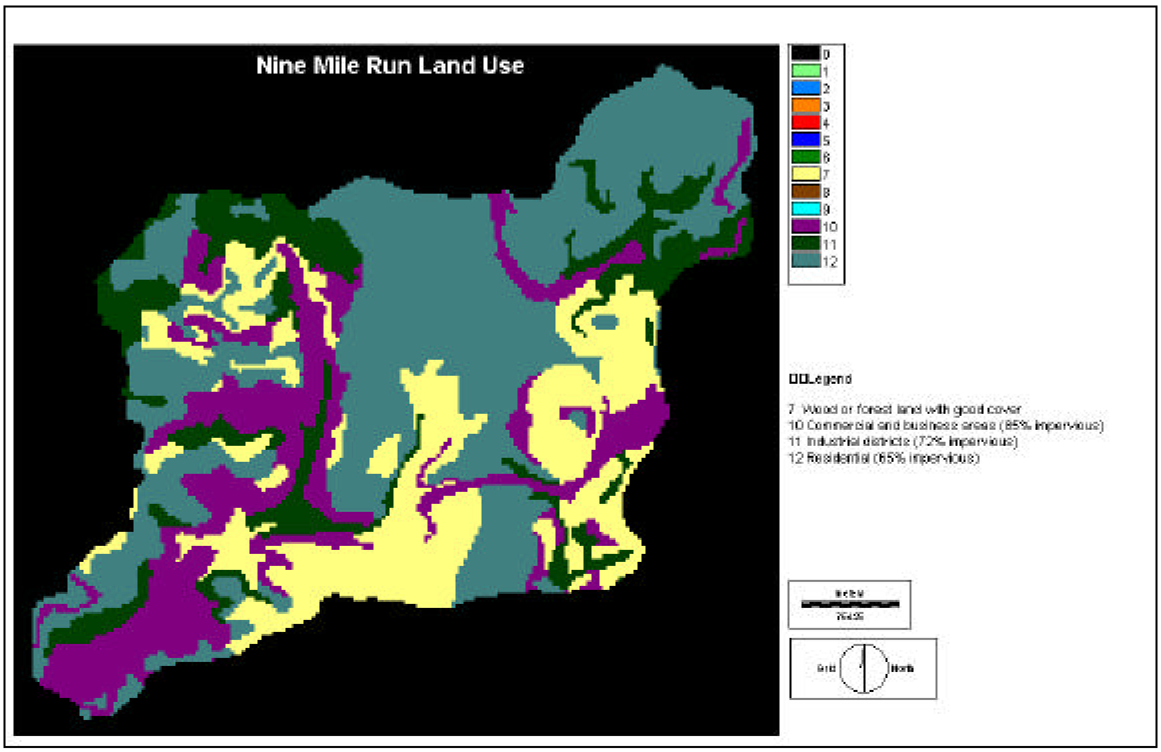

Figure 6-4 Land Use for Nine Mile Run Watershed

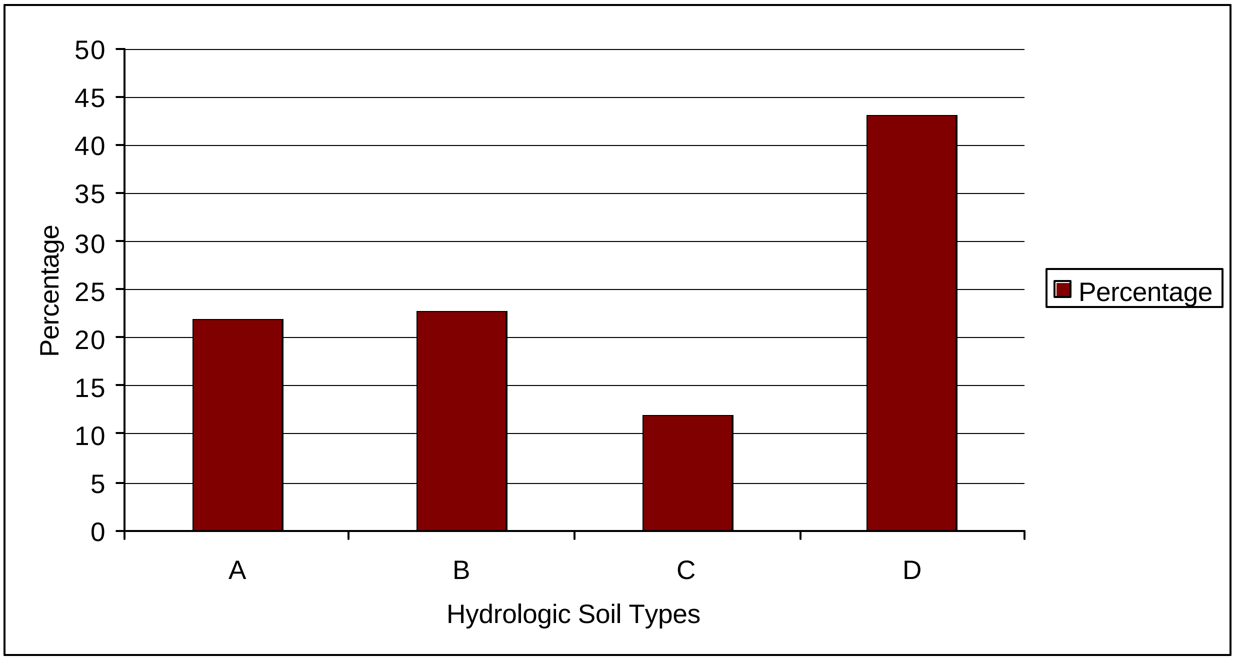

Figure 6-5 Distribution of the Hydrologic Soil Groups for Thompson Run Watershed

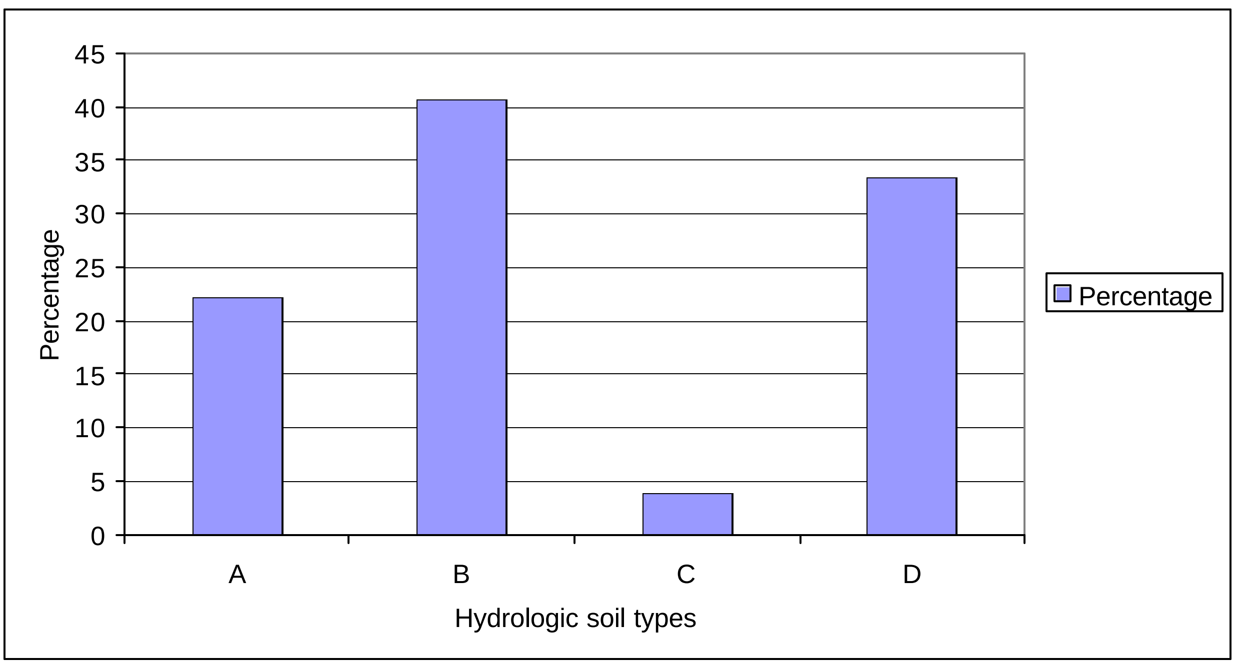

Figure 6-6 Distribution of the Hydrologic Soil Groups for Nine Mile Run Watershed

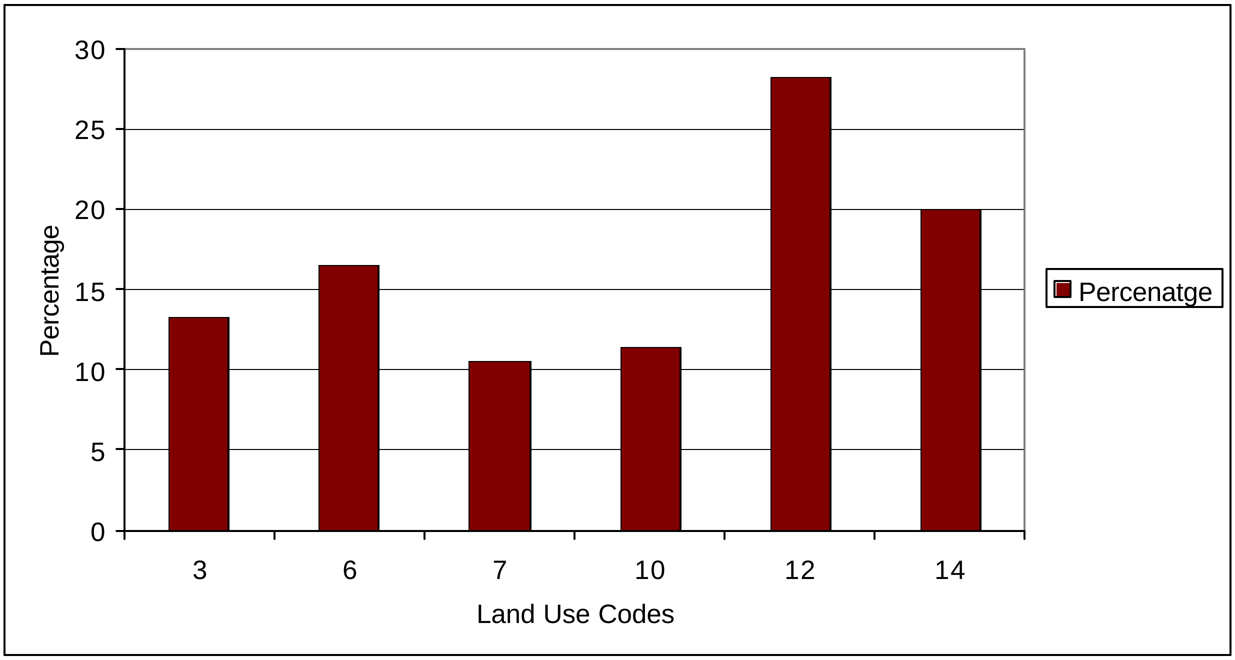

Figure 6-7 Distribution of Land Use for Thompson Run Watershed

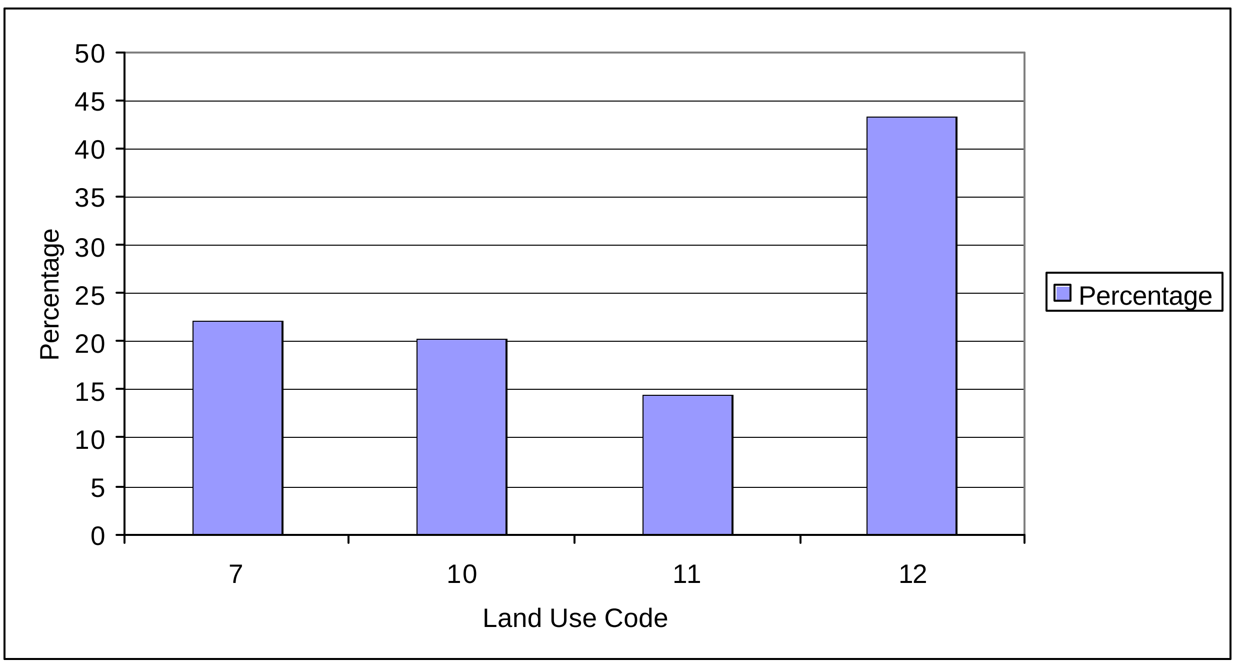

Figure 6-8 Distribution of Land Use for Nine Mile Run Watershed

6.2 DEM processing

The objective of DEM processing is to correct erroneous cell values to allow for the derivation of a correct hydrologic flow path.

6.2.1 Single Cell Depression Filling

A pit is a cell or group of cells completely surrounded by higher elevation cells. While naturally occurring pits exist on the earth's surface, many of the pits in the DEM are the byproduct of the DEM production process. The pits are removed by raising the elevation of the central cell to the elevation of the lowest neighboring cell. The artificial pits are recognized and removed by the PIT REMOVAL module of the GIS software IDRISI.

6.2.2 Flow Directions

The DEM corrected for the pits is then used in the determination of flow direction. The Fortran program DIRECT used in this research defines a single flow direction for each cell based on the direction of steepest descent from a given cell to one of the eight neighboring cells. The steepest descent is calculated as the elevation difference between the central cell and the adjoining eight cells divided by the distance of the center from the center. For the corner cells this distance is 1.414 times the cell size and for the side cells it is equal to the cell size. If the center cell happens to have it's elevation less than the adjoining cells it is a pit and hence it does not have a flow direction defined and hence it is assigned a negative value. If two cells have the same descent then the flow direction is assigned arbitrarily. The underlying assumption in this analysis is that each grid cell discharges all its flow to a single neighboring cell. Flow direction is denoted by a value assigned to each grid cell. Figure down shows the cell values assigned for the respective directions of flow.

The flow direction is an important component as it is a required input for the derivation of other components like watersheds, stream network and flow lengths, etc. It must consequently be checked for errors. One simple test is the computation of the histograms of the cell values. The presence of the cell values other than those shown in the figure denotes the presence of pits, which must be removed before proceeding any further.

6.2.3 Watershed Delineation

The watershed of the Digital Elevation model can be developed using the WATERSHED module of IDRISI, but this only marks out the watershed of a particular area, the threshold for which we specify while using the module. But if we need to mark out the sub watersheds in a big watershed we need to use the Fortran program WTRSHED. It takes the input as the number of rows and the number of columns in the elevation file, the direction file that we create using the Fortran program DIRECT and the watershed mask file. The mask file for the above input can be created as follows. First create a raster file (of the same size as the DEM that one is using) with the values as –1, this can be done using the INITIAL module. Then we need to update (using UPDATE module) this raster file with the rows and columns of the outlets of the sub watersheds that we need to delineate. This file is the mask file that one uses as input for running the WTRSHED program to delineate the watersheds. The following tables give the values that were used to in the UPDATE module.

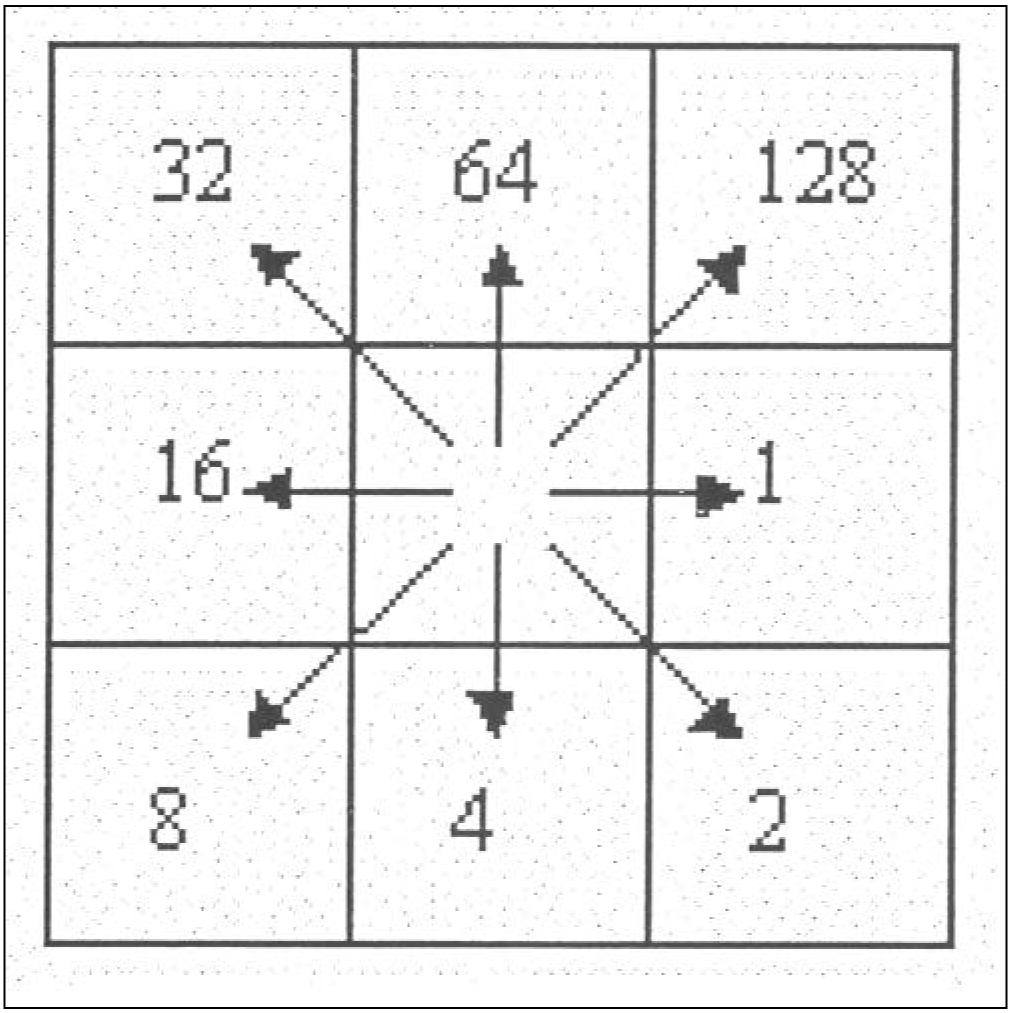

Figure 6-9 Flow Directions and Flow Numbers

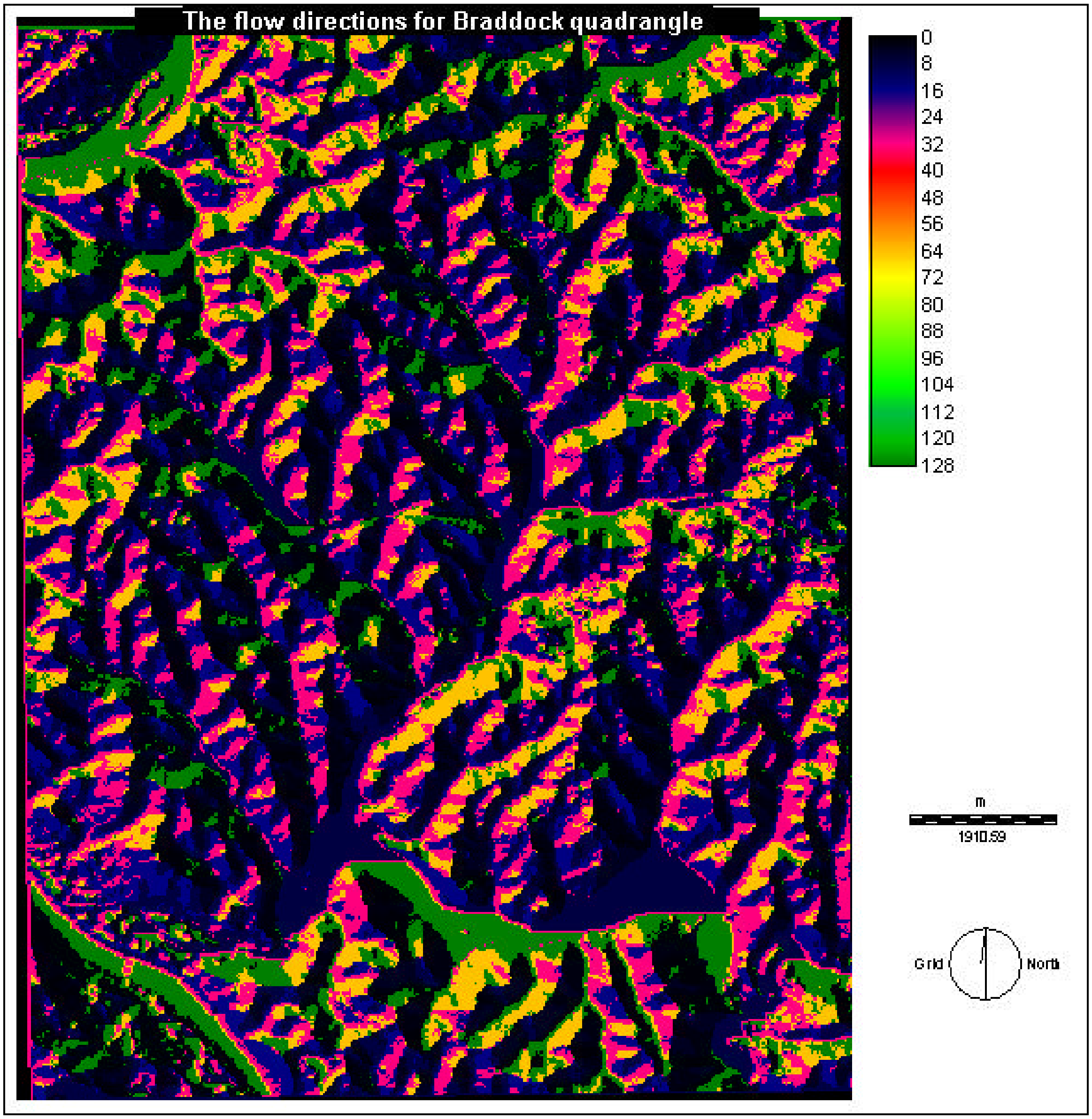

Figure 6-10 Flow Direction Raster File of Thompson Run Watershed

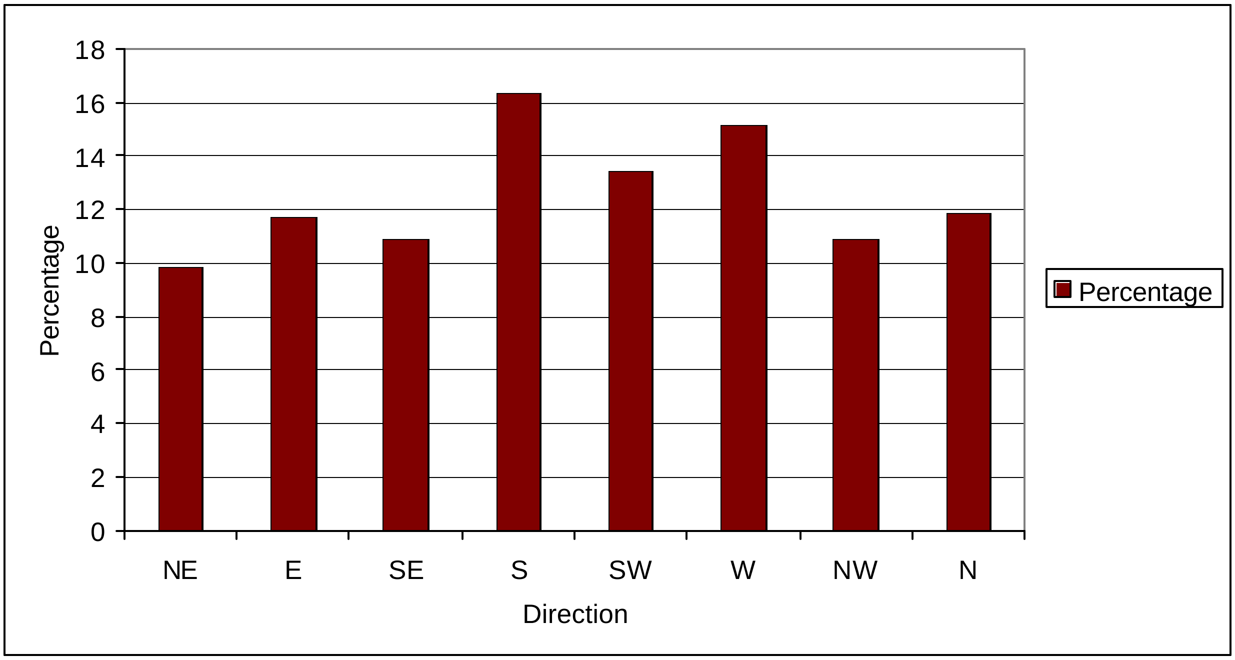

Figure 6-11 Flow Directions for Thompson Run Watershed

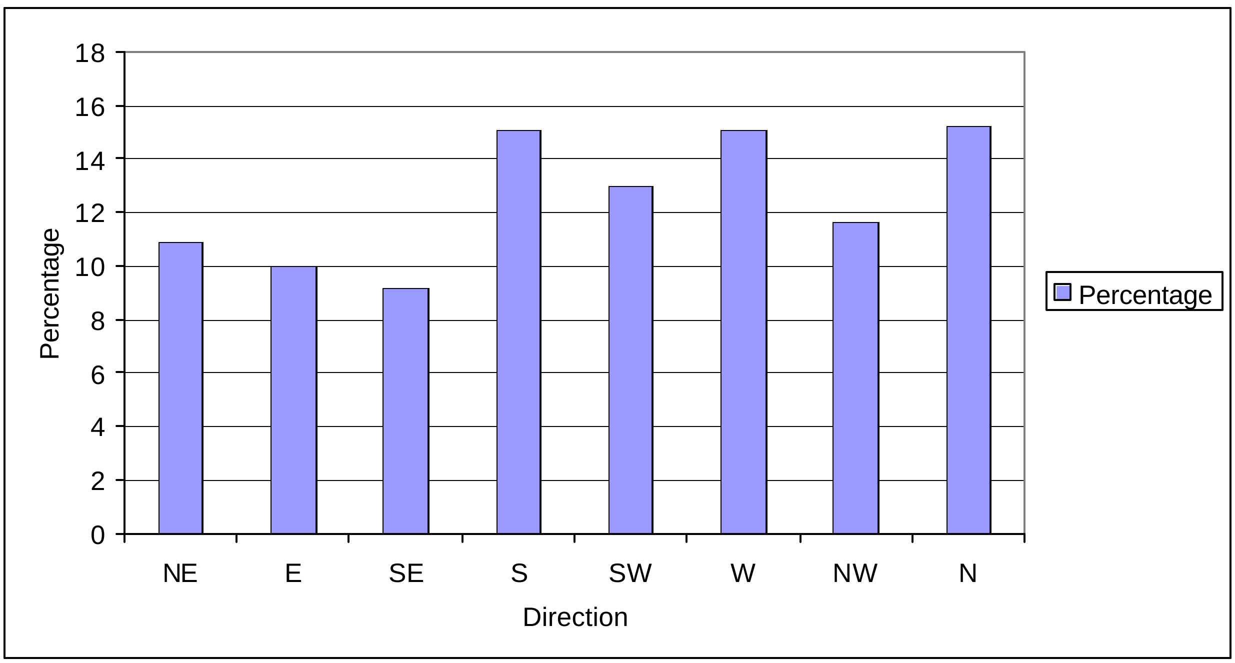

Figure 6-12 Flow Directions for Nine Mile Run Watershed

Table 6-1 Values used for creating the sub watersheds for Thompson Run

Value	**First row**	**Last row**	**First Column**	**Last Column**
1	363	363	143	143
2	292	292	171	171
3	212	212	224	224
4	214	214	222	222
5	213	213	221	221

Table 6-2 Values used for creating sub watersheds for Nine Mile Run

Values	**First row**	**Last row**	**First column**	**Last column**
1	326	326	105	105
2	273	273	141	141
3	278	278	159	159
4	227	227	184	184
5	232	232	171	171

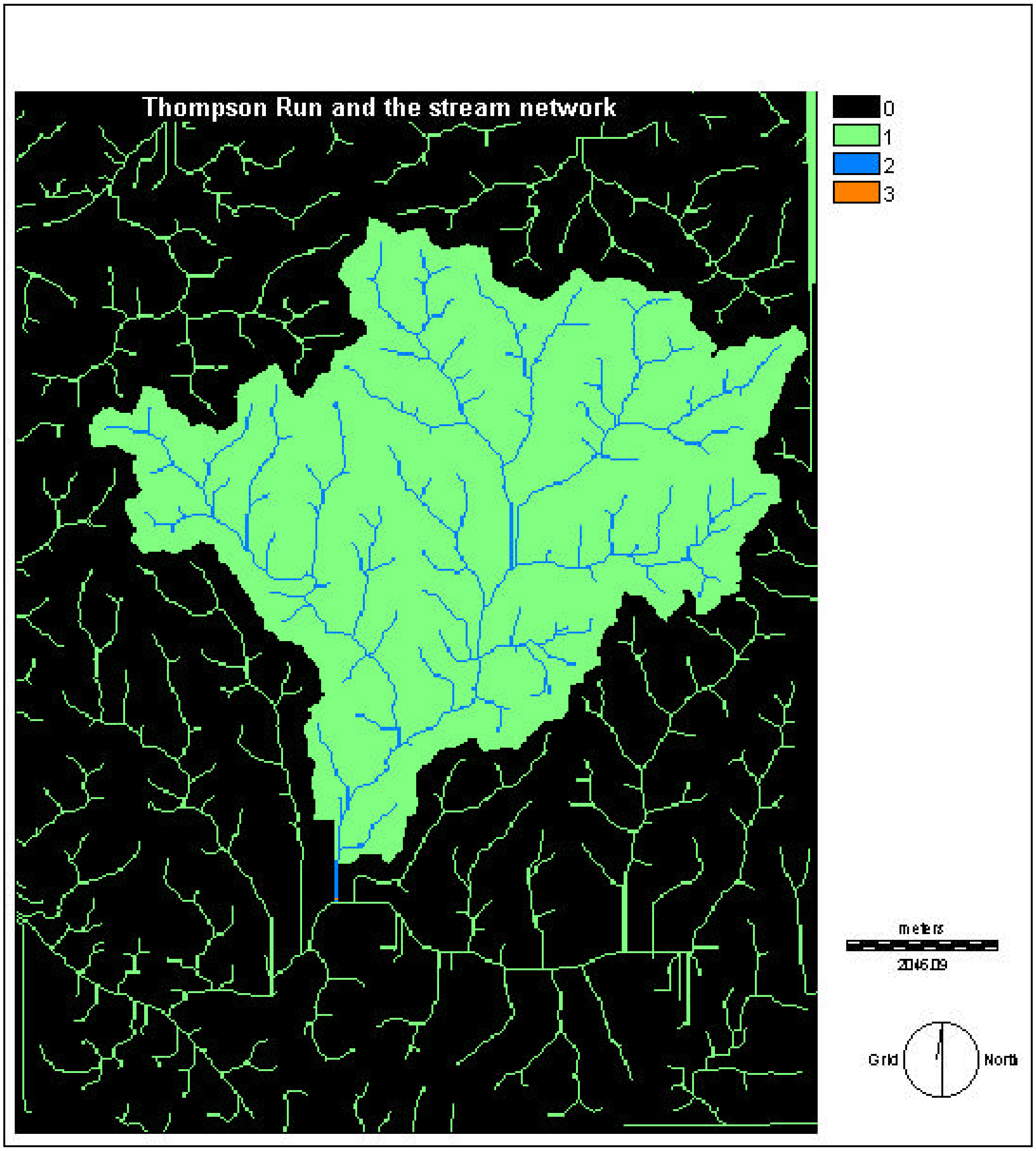

Figure 6-13 Thompson Run Watershed and the Stream Network

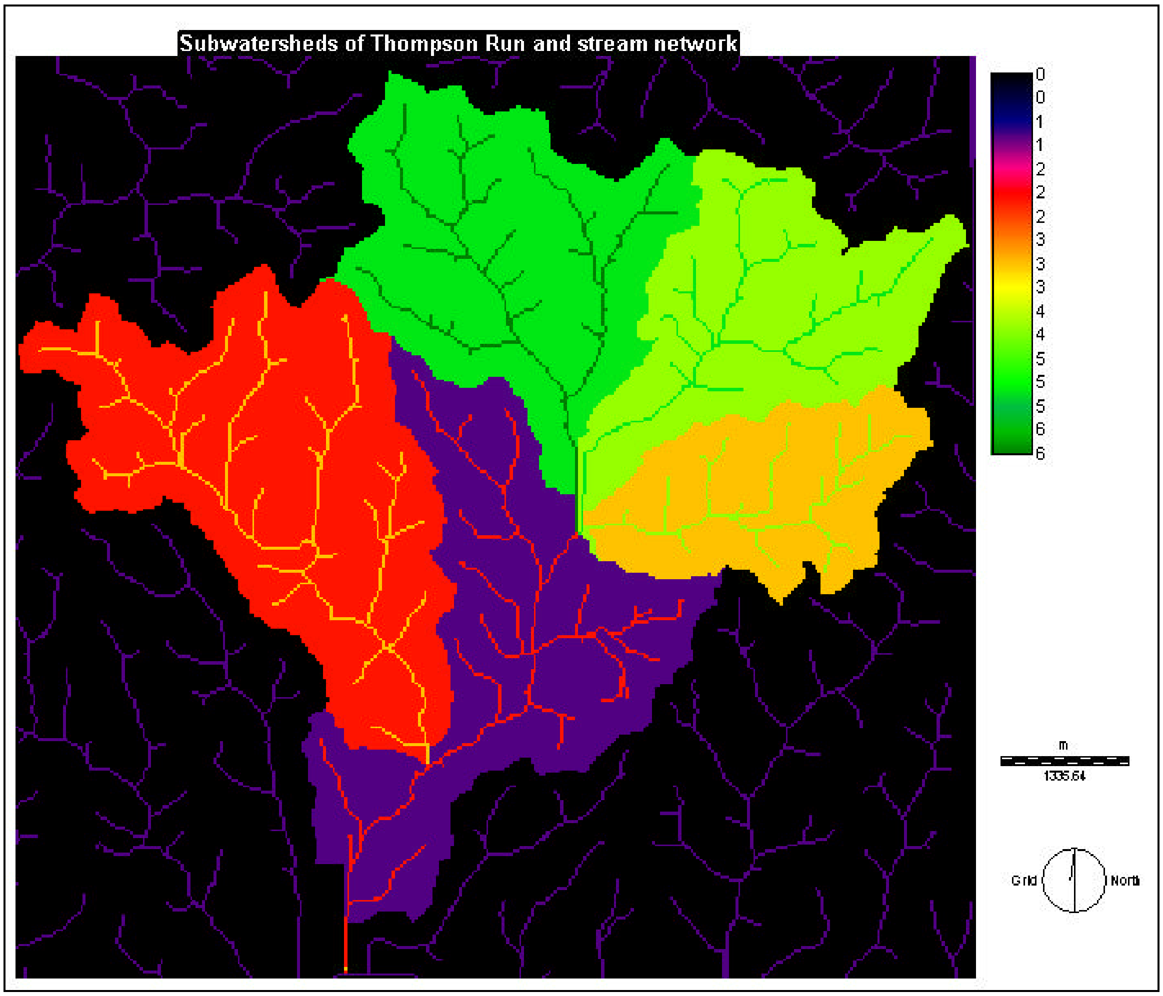

Figure 6-14 Sub-watersheds for Thompson Run Watershed

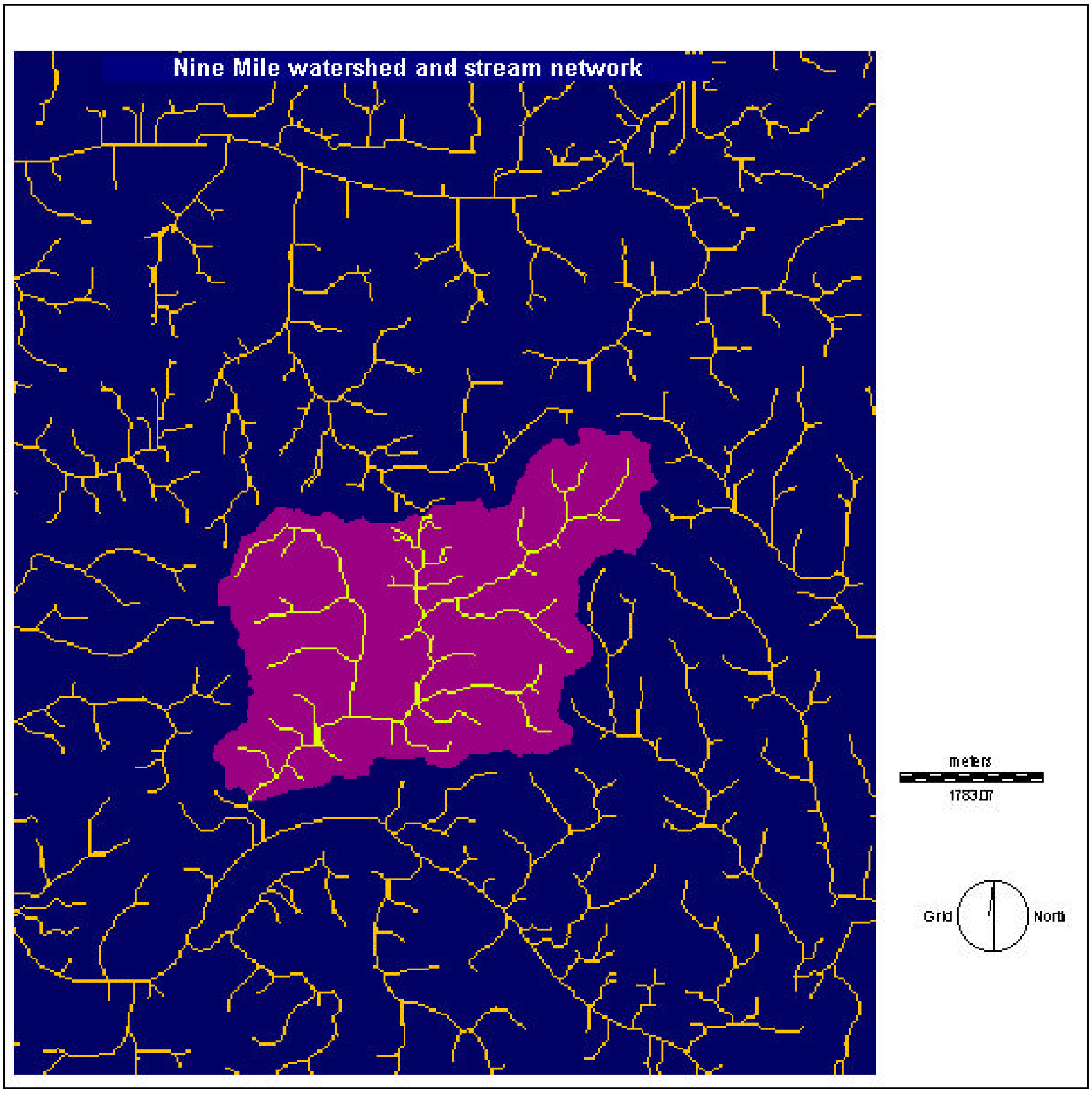

Figure 6-15   Nine Mile Run Watershed and Stream Network

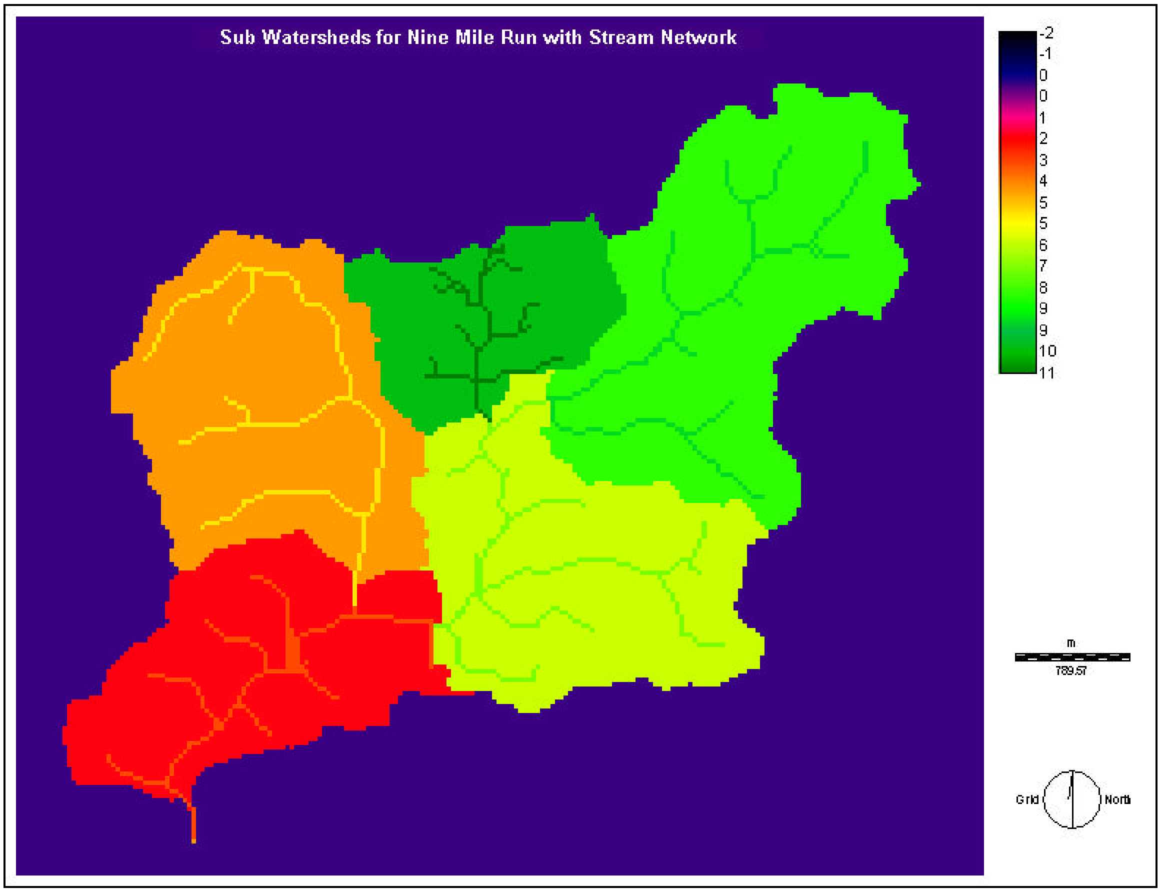

Figure 6-16 Sub-watersheds for Nine Mile Run Watershed

6.2.4 Precipitation Area

The area experiencing a particular value of precipitation can be developed using the Fortran program PREC_REAL_KNK. It takes the input as the number of rows and the number of columns in the elevation file, the direction file that we create using the Fortran program DIRECT and the precipitation mask file. The mask file for the above input can be created as follows. First create a raster file (of the same size as the DEM that one is using) with the values as –1.0 (remember this file will have real values), this can be done using the INITIAL module. Then we need to update (using UPDATE module) this raster file with the rows and columns of the lower left hand corner of the area that would have a particular value of the precipitation. This file is the mask file that one uses as input for running the PREC_REAL_KNK program to mark out the precipitation areas. If we use the same values as given in the tables above that would create the precipitation areas that would have the same area as the sub watersheds with values 1.0, 2.0, 3.0, 4.0 and 5.0.

6.2.5 Flow distance

The flow distance is the distance that a drop of rain has to travel in each cell. If the flow direction value of the adjoining cell happens to be 2,8,32 or 128 then the flow distance is the size of the grid otherwise it is equal to root 2 times the size of the grid.

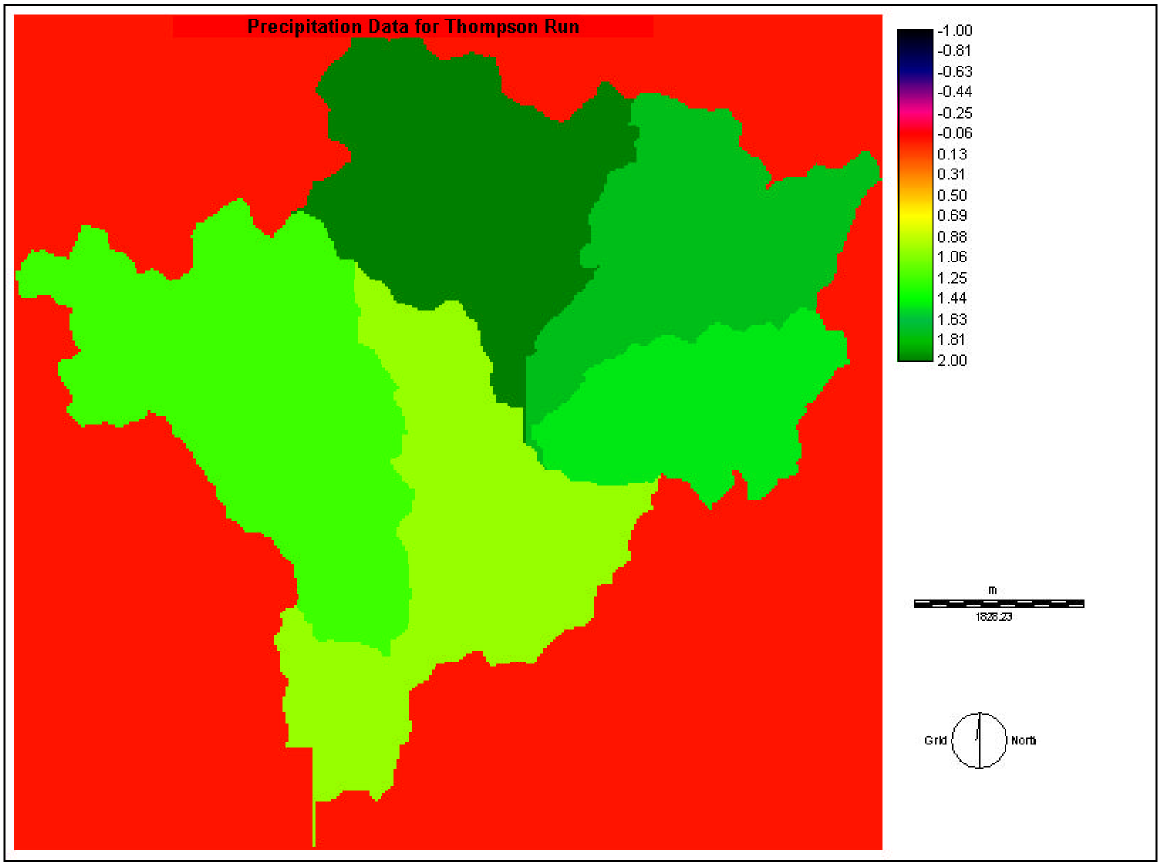

Figure 6-17 Precipitation file for Thompson Run Watershed

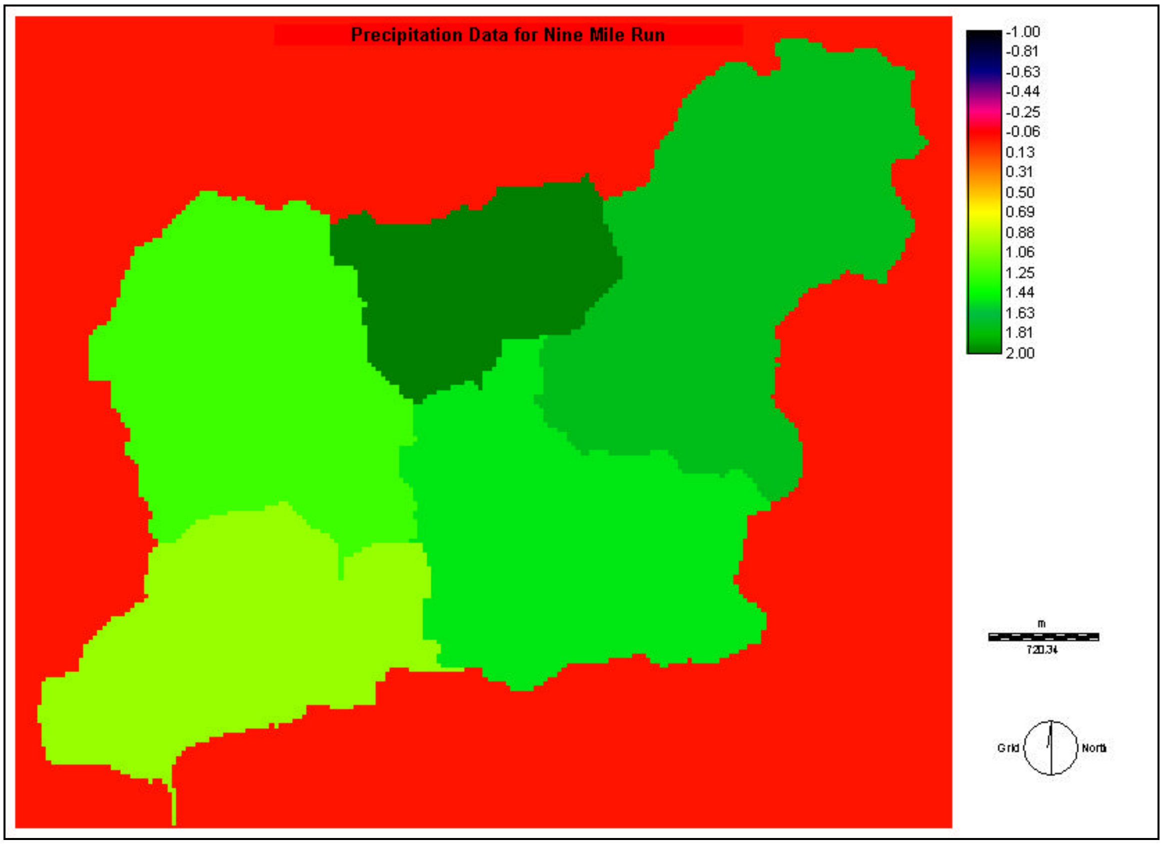

Figure 6-18 Precipitation File for Nine Mile Run Watershed

6.2.6 Slope Calculation

The slope of each of the cell or flow-path is calculated by finding the difference in the elevation of the cell and the elevation of the outlet and dividing it by the distance of the source from the outlet. This is the slope that is used to establish the time lag for that flow path using the SCS method.

6.2.7 Stream generation

The stream network for the watershed can be generated using either the inbuilt module of IDRISI or the Fortran program CHANNEL. The technique is to count the number of cells draining into each cell based on the flow direction. The program RCOUNT generates a file that stores the number of cells draining into each cell. The user needs to provide the threshold area that needs to drain into a cell to make it a channel cell. This threshold area is a function of the watershed characteristics like soil type and slope etc. For this study it was found that 100 cells or an area of 22 acres provided good enough results.

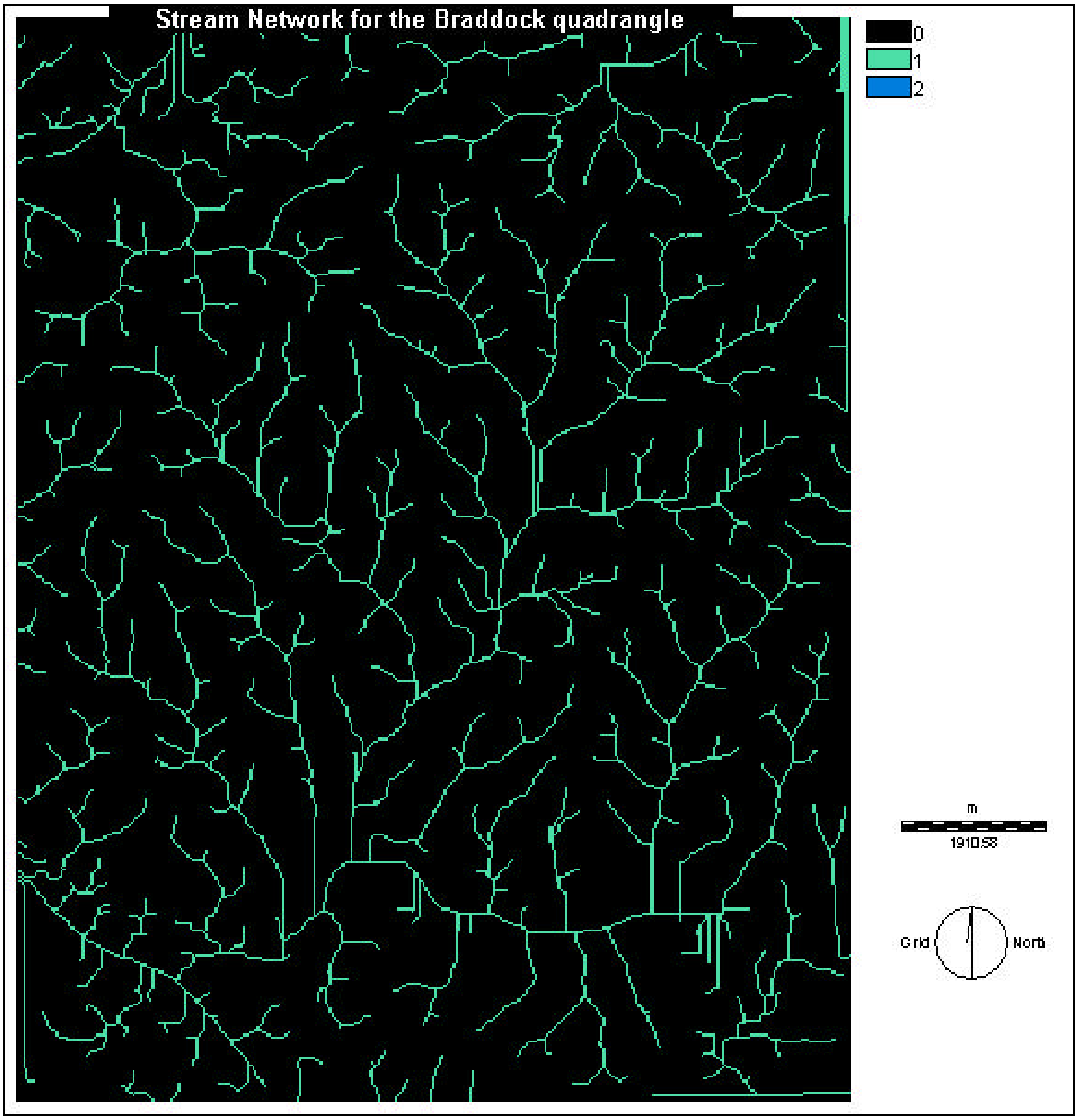

Figure 6-19 Stream Network file for Thompson Run Watershed

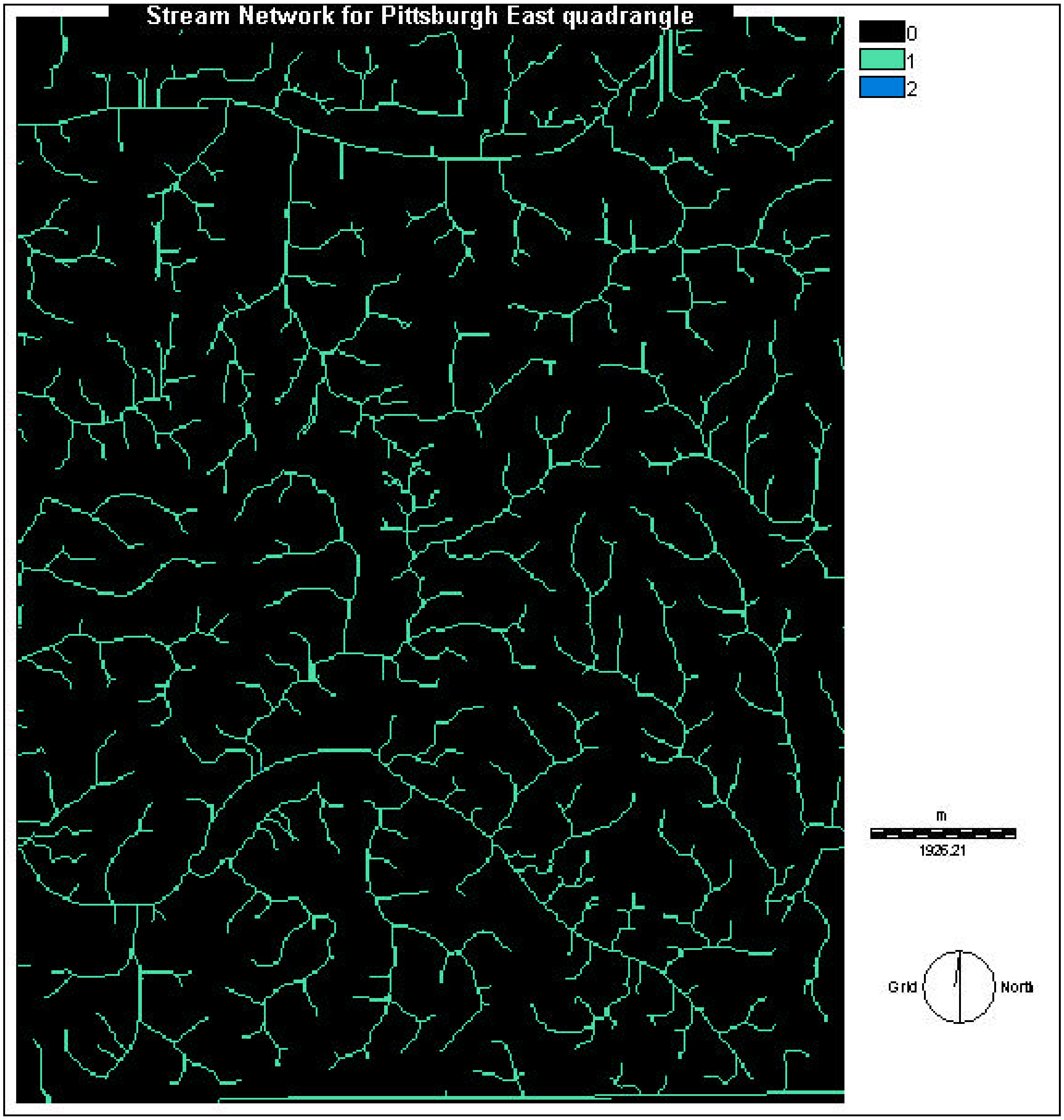

Figure 6-20 Stream Network for Nine Mile Run Watershed

6.3 Flow Velocities for Isochrones Generation

Isochrones are the lines that divide the watershed into areas with the same time of travel. It is assumed that the cells falling in one sub area between two isochrones has the same uniform velocity. A cell in the watershed may have different velocities depending on the kind of flow it experiences, either overland flow or channel flow. The overland flow is dependent on the Manning's n and the channel flow is dependent on the cross section of the channel. To obviate the subjectivity that might result due to these varying conditions it was thought to use the SCS (1986) curves of average velocities of overland flow depending upon the curve number of the watershed. The curve number was used to determine the velocity, as that was the database developed for the study. Using the velocity curves different formulas were worked out which operated in a given range of the curve numbers. Though this method has no theoretical basis, it produced acceptable results. The formulas and the range of the curve numbers in which they apply are presented Table 6-3:

Table 6-3 Formulas for the calculating velocity for isochrones generation and range of the Curve Numbers in which they are used

Range of CN	Velocity formula
0 – 50	$y = 0.041e^{0.2951x}$
51 –60	$y = 0.0813e^{0.2836x}$
61 – 70	$y = 0.1217e^{0.2861x}$
71 – 75	$y = 0.1686e^{0.2882x}$
76 – 85	$y = 0.2533e^{0.2925x}$
86 - 100	$y = 0.3378e^{0.2885x}$

y gives the velocity in m/sec

x is the slope in percentage

6.4 Travel time

The travel time for each cell is computed using the lag time estimation relation developed by the SCS in 1973.

$$t_L = 0.6t_C \tag{6-1}$$

where

t_C is the time of concentration for the watershed and t_L is the lag time given by

$$t_L = \frac{L^{0.8}\left[\left(\frac{1000}{CN} - 10\right) + 1\right]^{0.7}}{1900 S^{0.5}} \qquad (6\text{-}2)$$

where

L is the length of the flow path in feet

S is the slope in percentage

CN is the curve number

t_L is the lag time in hours

The slope for each of the cells is calculated and so is the distance of the cell from the outlet of the watershed. The individual curve number for the cell is identified from the curve number file and is used to calculate the retention factor for that cell. Thereby the lag time and hence, the time of concentration of the cell is worked out. This travel time for each cell is recorded and is used to develop the time area histogram for the watershed.

6.5 Curve Number

To effectively accomplish the spatial distribution of the watershed characteristics the curve number file for the watershed was developed using the land use and soil type data files. The SCS has classified more than 4000 soils into four hydrologic soil groups according to their minimum infiltration rate obtained for bare soil after prolonged wetting. The four hydrologic groups are denoted by letters A, B, C and D (Haan et al.,1994)[(32)]. Since we need to create raster files for the soil type each group was given an integer value for reference.

Table 6-4 Integer values assigned to different Hydrologic Soil Groups

Group	Reference Integer
A	1
B	2
C	3
D	4

In the same way each land use was also given an integer value and its raster file created. These two raster files were the inputs for the CURVE_NUMBER_KNK Fortran program, which generated the curve number raster file in which each cell has a curve number value assigned to it depending upon the soil type and the land use it had.

Table 6-5 Soil Textures for different Hydrologic Soil Groups

HSG	Soil Texture
A	Sand, loamy sand, or sandy loam
B	Silt loam or loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay

Table 6-7 gives the curve numbers for some selected land uses, this table also shows the integer values that different soil types and different land uses were assigned for the calculation of the curve numbers. Curve number values range from 0 to 100. If the value is 0 then no runoff is generated while if the curve number is 100 all the rainfall is transformed into runoff without any abstractions

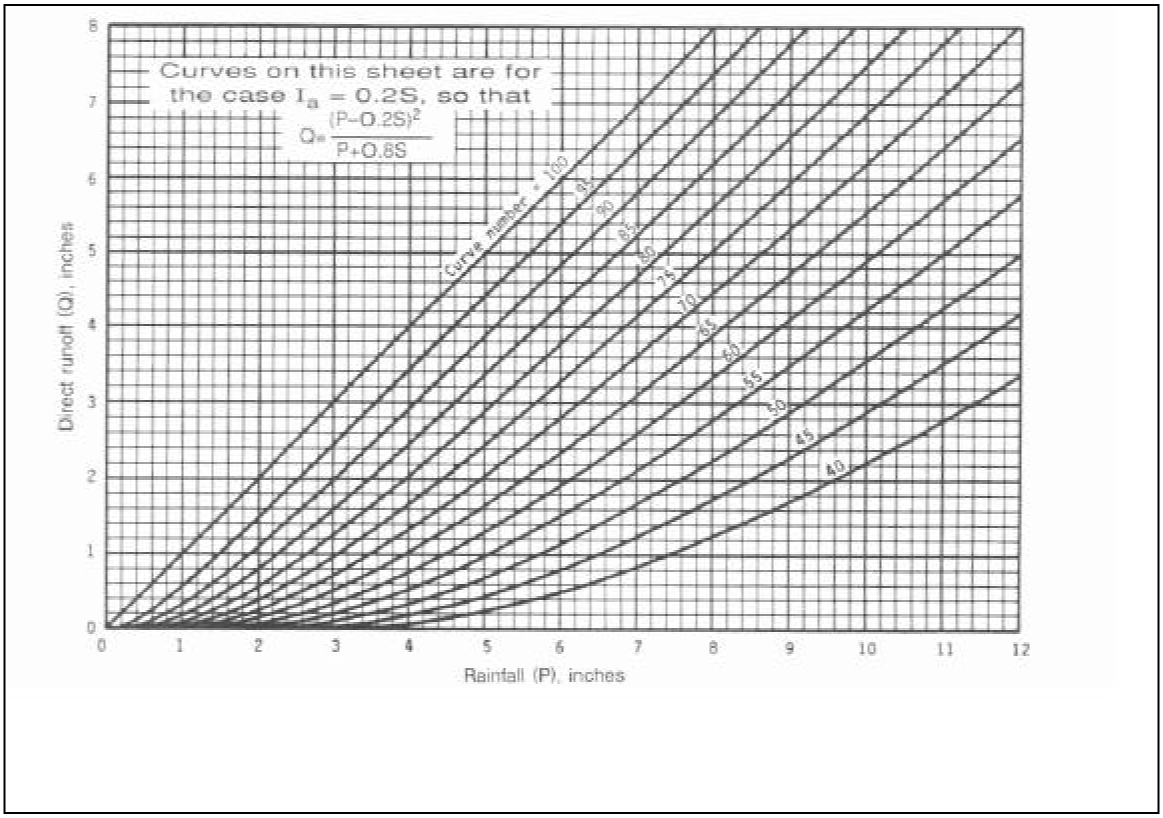

Figure 6-21 Rainfall , Runoff generated and the Curve Numbers

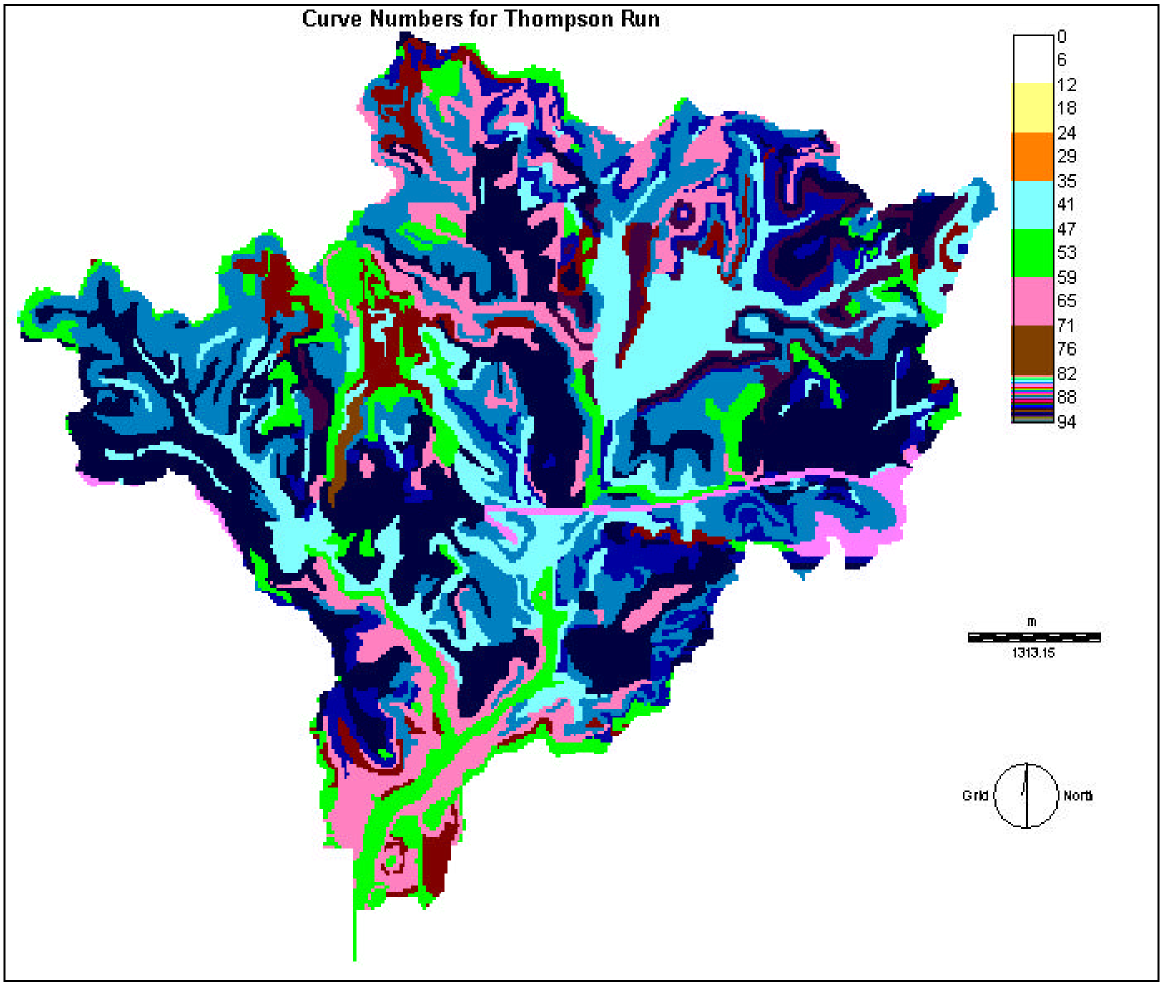

Figure 6-22 Curve Numbers for Thompson Run Watershed

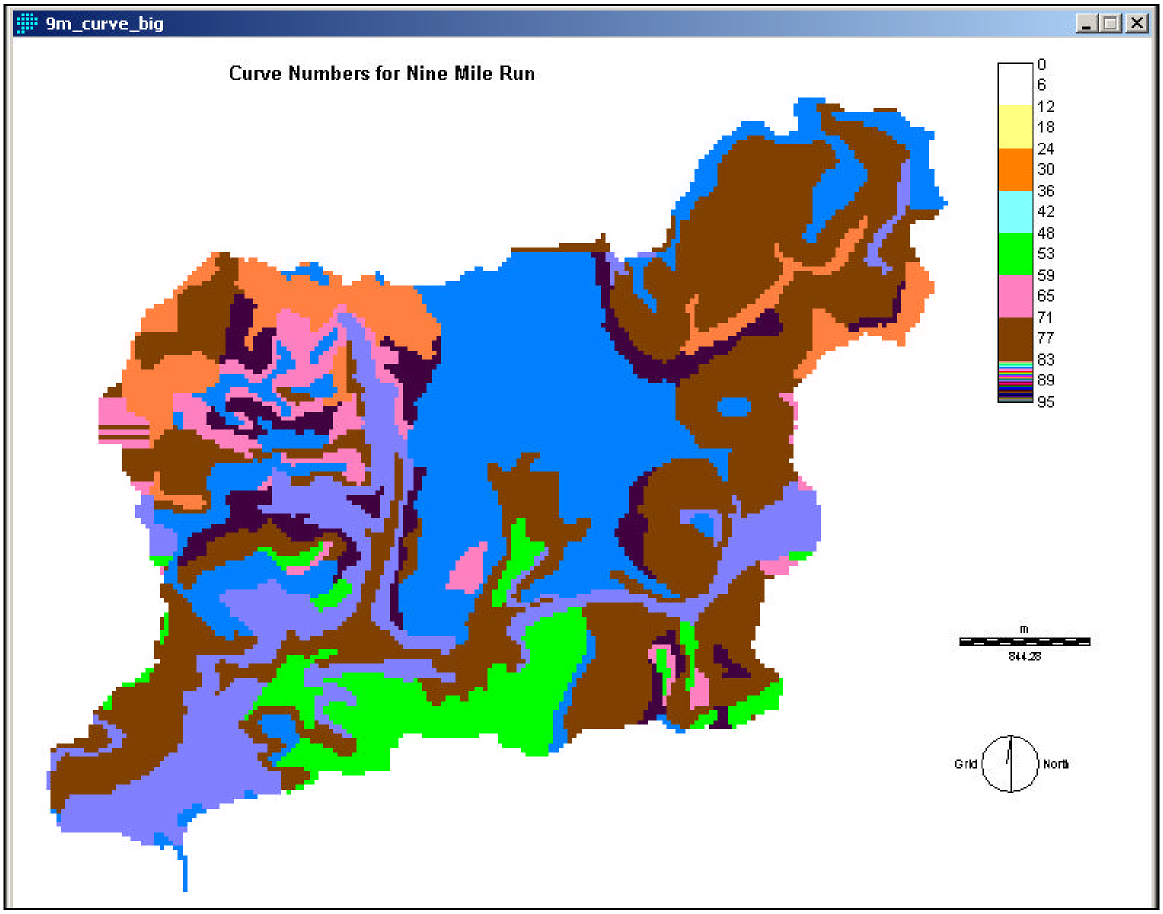

Figure 6-23 Curve Numbers for Nine Mile Run Watershed

Table 6-6 Definition of SCS Hydrologic Soil Groups (Soil Conservation Service, 1986)

Group A – soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sands and gravels and have a high rate of water transmission (greater than 0.30 in/hr).

Group B – soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.15 – 0.30 in/hr).

Group C – soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (0.05 – 0.15 in.hr).

Group D – soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0.0 – 0.05 in/hr).

Some soils in the list are in group D because of a high water table that creates a drainage problem. Once these soils are effectively drained, they are placed in a different group. For example, Ackerman soil is classified as A/D. This indicates that the drained Ackerman soil is in group A and the undrained soil is in group D.

Table 6-7 Runoff Curve Numbers for Selected Land Uses
(Soil Conservation Services, 1986)

		Hydrologic Soil Group				
	Soil#	*1*	*2*	*3*	*4*	
Land use description		A	B	C	D	Lu#
Cultivated land						
Without conservation treatment		72	81	88	91	*1*
With conservation treatment		62	71	78	81	*2*
Pasture or range land						
Poor condition		68	79	86	89	*3*
Good condition		39	61	74	80	*4*
Meadow						
Good condition		30	58	71	78	*5*
Wood or forest land						
Thin stand, poor cover, no mulch		45	66	77	83	*6*
Good cover		25	55	70	77	*7*
Open spaces , lawns, parks, etc.						
Good condition (grass cover on 75% or more of the area)		39	61	74	80	*8*
Fair condition (grass cover on 50 to 75% of the area)		49	69	79	84	*9*
Commercial and business areas(85% impervious)		89	92	94	95	*10*
Industrial districts(72% impervious)		81	88	91	93	*11*
Residential						
Average lot size	Average % impervious					
1/8 acre or less	65	77	85	90	92	*12*
¼ acre	38	61	75	83	87	*13*
1/3 acre	30	57	72	81	86	*14*
½ acre	25	54	70	80	85	*15*
1 acre	20	51	68	79	84	*16*
Paved parking lots, roofs, driveways, etc.		98	98	98	98	*17*
Streets and roads						
Paved with curbs and storm sewers		98	98	98	98	*18*
Gravel		76	85	89	91	*19*
Dirt		72	82	87	89	*20*

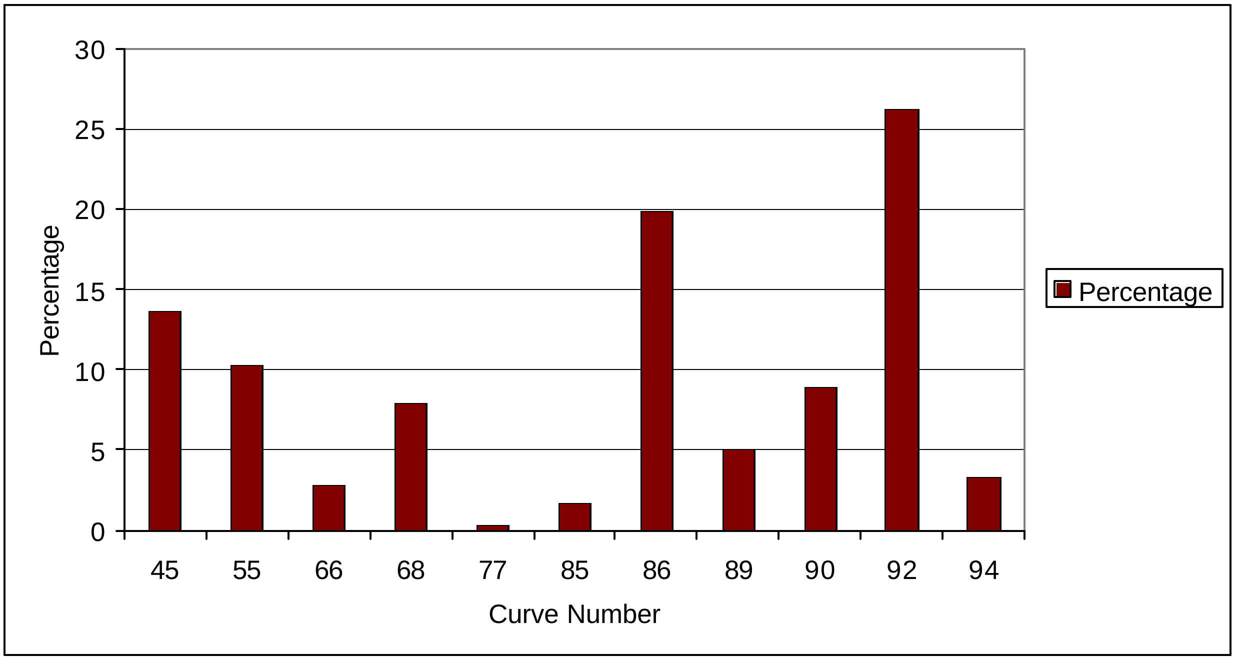

Figure 6-24 Curve Number distribution for Thompson Run Watershed

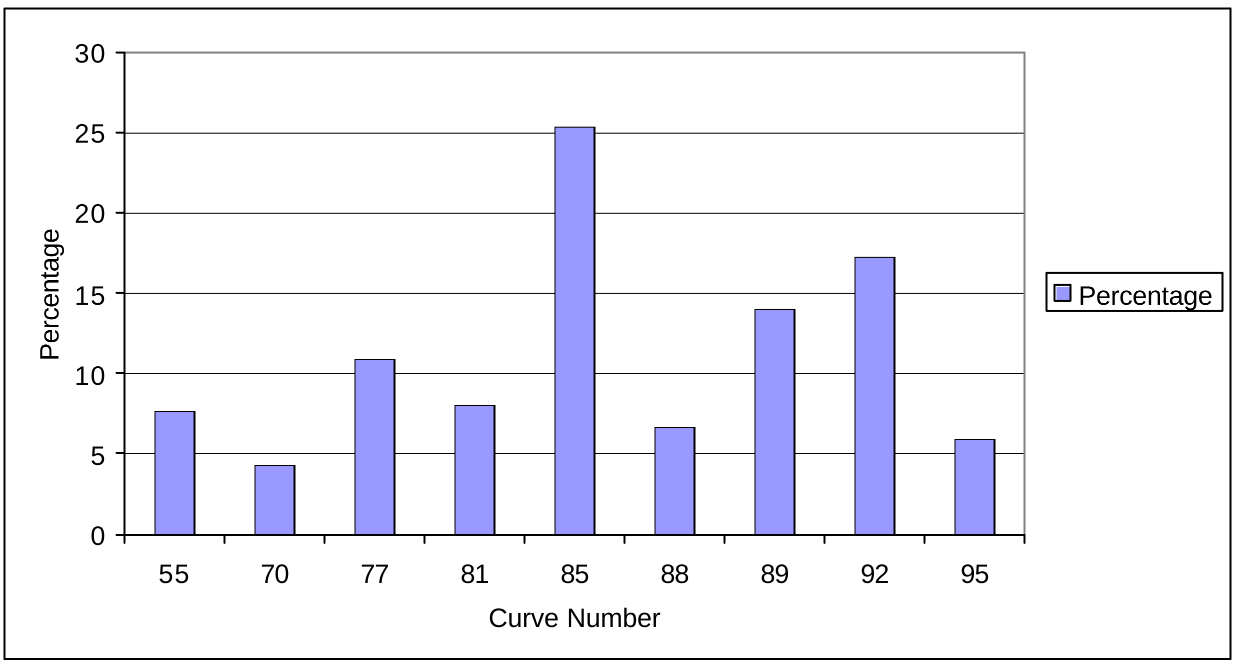

Figure 6-25 Curve Number distribution for Nine Mile Run Watershed

6.6 Runoff Calculation

Accurate rainfall estimates during a storm event are invaluable to a forecaster responsible for the flood warnings and reservoir operations, especially if he is required to predict actual flows within the next several hours. Traditionally, rain gauges have been used for measuring precipitation and telemetry used for transmitting real time records from remote gauges to the forecast office. The main drawback with the gage information is that the record is made at a point and then an interpolation scheme is used to calculate the average watershed rainfall. As the time period for analysis decreases, the interpolation becomes more and more unreliable as short duration rainfall data is less spatially correlated than the long duration rainfall data. This limitation can be overcome if the gridded precipitation data produced by the National Weather Service (NWS) under their Next Generation Weather Radar (NEXRAD) program, can be incorporated into a spatially distributed hydrologic model.

The model developed in the study not only covers the spatial variability of the watershed characteristics like soil type and land use but also the spatial distribution of the rainfall in the watershed. In the absence of the real time data, for demonstration purposes, hypothetical rainfall data was created in form of raster files. Each cell of the precipitation raster file has the value of the precipitation that is assumed to be falling in that cell. This precipitation value is read and then using the method described below the runoff generated in each cell is calculated.

Rainfall excess, or equivalently, the runoff volume can be calculated using the relationship developed by the SCS in 1972. This method uses the curve numbers for the estimation of the runoff. The curve number of the cell indicates the runoff potential of the cell.

Since it is an overtly simplified method it has it's limitation and hence it provides results that are less accurate than more detailed processes (SCS, TR-55, 1986)[33].

$$S = \frac{1000}{CN} - 10 \tag{6-3}$$

$$I_a = 0.2S \tag{6-4}$$

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{6-5}$$

where

S is the maximum retention after the runoff begins (inches)

CN is the curve number

Ia is the initial abstraction

P is the rainfall in inches

Q is the runoff in inches

It is to be noted that P must exceed 0.2S before any runoff is generated. This equation is a runoff equation and not an infiltration equation. It would result in errors if it were used for infiltration calculations(Haan et al.,1994)[32].

The runoff volume for all the cells falling in a particular time interval is added up. This gives a runoff-time histogram, which is then utilized to create the runoff hydrograph for the watershed.

6.7 Limitations of the Curve Number Method

The TR-55 curve number method has the following limitations which have been produced from TR-55 Figure 4.

- Curve numbers describe average conditions that are useful for design purposes. If the rainfall event used is a historical storm, the modeling accuracy decreases. Use the runoff curve number equation with caution when recreating specific features of an actual storm. The equation does not contain an expression for time and, therefore, does not account for rainfall duration or intensity.
- The user should understand the assumption reflected in the initial abstraction term(Ia) and should ascertain that the assumption applies to the situation. Ia, which consists of interception, initial infiltration, surface depression storage, evapotranspiration, and other factors was generalized as 0.2S based on data from agricultural watersheds (S is the potential maximum retention after runoff begins). This approximation can be especially important in an urban application because the combination of impervious areas with pervious areas can imply a significant initial loss that may not take place. The opposite effect, a greater initial loss, can occur if the impervious areas have surface depressions that store some runoff. To use a relationship other than Ia=0.2S, one must redevelop equation 2-3, figure 2-1, table 2-1, and table 2-2 by using the original rainfall-runoff data to establish new S or CN relationships for each cover and hydrologic soil group. Runoff from snowmelt or rain on frozen ground cannot be established using these procedures.

- The CN procedure is less accurate when the runoff is less than 0.5 inch . As a check, use another procedure to determine runoff.
- The SCS runoff procedures apply only to direct surface runoff: do not overlook large sources of subsurface flow or high ground levels that contribute to runoff. These conditions are often related to HSG A soils and forest areas that have been assigned relatively low CN's in table 2-2. Good judgment and experience based on stream gage records are needed to adjust Cn's as conditions warrant.
- When the weighted CN is less than 40, use another procedure to determine runoff

6.8 Hydrograph Generation

The runoff hydrograph is developed using the time – runoff histogram. As mentioned in the STS routing technique (section 3.1.5) since the source or each individual cell in the watershed is not connected to the sink or the outlet of the watershed the use of linear routing cannot be justified. It was thus thought appropriate to use the lag and route technique. It is assumed that each portion of the time – runoff diagram represents the outflow from that sub-area of the watershed, which is lagged by the duration of the time interval between two consecutive isochrones. Thus each portion of the time – runoff diagram is routed using the Reservoir Routing method. The storage constant was approximated to be equal to the time of concentration for the watershed under consideration. Although the time – runoff diagram was obtained using the spatial distributed model the routing was performed as if for a lumped model.

CHAPTER 7

7.0 RESULTS

To achieve the objectives mentioned before in section 1.2 additional Fortran programs were written and some old ones from the previous study were modified. Using the soil raster file and the land use raster file the curve number raster file is developed which is then used in the MOD_TA&EX_V+SCS Fortran program which does almost all of the analysis and produces the results. The MOD_TA&EX_V+SCS program takes the following files and values as input.

11) The number of rows and columns in the elevation file.
12) The elevation file corrected for the single cell depressions.
13) The watershed file.
14) The stream network file.
15) The flow direction file.
16) The isochrones file.
17) The precipitation file.
18) The curve numbers file.
19) The grid size of the Digital Elevation Model.
20) The number of the watershed to be analyzed.
21) The average value of the curve number of the watershed for developing the isochrones.
22) The time interval for the time area diagram in minutes.

The average value of the curve number for the watershed being analyzed is obtained from the data file generated as an output from the CURVE_NUMBER_KNK Fortran program. The

Fortran program MOD_TA&EX_V+SCS is used when one is working with the distributed curve numbers (that is using the Curve Number raster file). If one needs to work with only a single Curve Number for the whole watershed, one should use the program MOD_TA&EX_V+SCS_CONST_CN. The output generated by both the programs consists of the following files.

1) The data file (DATA.TXT), which outlines the values for the different watershed parameters and the areas having different times of travel to the outlet.
2) The time area file (TA.TXT), which has the total numbers of cells in different time intervals, this file is used to develop the time area diagram which can then to used to develop the unit hydrograph if required.
3) The runoff time file (EX_PREC.TXT), which has the total amount of runoff generated and the particular time it takes to surface at the output. This file is used by another program to develop the direct runoff hydrograph.
4) The bookkeeping file, (RECORD.TXT), which contains all the details of the processing that took place at each step. It keeps record of what values were read into the program and what new values were generated.
5) The isochrones raster file for the watershed in question.

The EX_PREC.TXT file is then used in the MUS_HYDRO_EXPREC_KNK program to generate the direct runoff hydrograph.

In the absence of the real time precipitation data, test data for precipitation is created in form of raster files, which have the same boundaries as the watersheds and the sub-watersheds but different areas have different precipitation so that the effect of the spatial distribution of precipitation can be outlined. The study also uses a spatially distributed curve numbers raster file where each cell has a different curve number and so the runoff created in different cells is different.

The program uses the watershed number inputted to identify the watershed to be processed in the watershed file. Using this watershed file as a template, it then identifies cells in the different files like the stream file, direction file, precipitation file and the curve number file. It locates the outlet for the watershed using the stream file. It then uses the different parameters read for the cell in different files to calculate the distance, velocity and the travel time to the outlet and also the amount of runoff being generated in that cell. Depending upon the travel time calculated it develops the time area coordinates, the runoff time coordinates and the isochrones.

The results were obtained for two watersheds, namely the Nine Mile Run watershed (Figure 7-1 to 7-18) and the Thompson Run watershed (Figure 7-19 to Figure 7-42). Each of the bigger watersheds was then divided into five sub watersheds. The analysis was carried out for the big watershed and the sub-watersheds for both the cases, and then the resulting hydrographs were compared. As one of the objectives of the study, the isochrones for the big watersheds and also the sub watersheds for both the watersheds were generated. The hydrographs generated for the individual sub watersheds for both the watersheds were then routed to the outlet of the bigger watersheds and the results compared. For the Nine Mile Run the comparison of the hydrographs for the routed sub watersheds and the big watershed is given in Figure 7-11 and Figure 7-13 and the comparison for the Thompson Run watershed is given in Figure 7-27 and Figure 7-29.

The study also observes the effect of the storage constant used in the linear routing. Two storage factors were used in this study, one that equaled the time of concentration in the watershed and the other was arbitrarily chosen as 30 minutes. Larger values of the storage constant (equaling the time of travel for the watershed) greatly reduced the peak value of the hydrograph, it produced a large attenuation of the flow. The time of peak remained nearly the same for both the storage constants.

Further more, results were developed for both the watersheds using the curve number file (with distributed curve numbers) and with a single value of curve number for the whole watershed to demonstrate the effect of the spatial distribution of the watershed response parameter. Hydrographs were also generated to demonstrate the effect of the spatial distribution of the precipitation along with the spatial distribution of the curve numbers.

The effect of the resolution of the DEM or the grid size was also studied for the Thompson Run watershed. Since the formula that is being used to calculate the lag time, takes into consideration only the distance of the individual cells from the outlet, the results show little if no difference. The reason being when we increase the resolution and hence reduce the grid size, although the cell size decreases, but at the same time the number of cells also increases and hence the overall effect of increasing or reducing the resolution is lost. These results are presented in form of a comparison of the hydrographs developed for the three resolutions studied namely grids of 15m, 30m and 120m in Figure 7-52. Table 7-1 gives the values for the number of cells and the time taken to process Thompson Run watershed at different resolutions:

Table 7-1 Effect of Resolution on Time and Cell count

Grid Size	**Number of Cells**	**Time to process**
15 meters	181820	33 hrs 35 min
30 meters	45455	35 min
120 meters	2840	3 min

7.1 Results for Nine Mile Run Watershed

```
             THE CURVE-NUMBER CALCULATION FILE
             ---------------------------------


WATERSHED NUMBER:  1


NUMBER OF CELLS IN THE WATERSHED:     17243



CURVE NUMBER                        NUMBER OF CELLS
------------                        ---------------
     55                                  1315
     70                                   742
     77                                  1878
     81                                  1382
     85                                  4372
     88                                  1153
     89                                  2414
     92                                  2968
     95                                  1019


      CURVE NUMBER FOR THE WATERSHED: 84
```

Figure 7-1 Curve Number file for Nine Mile Run

```
WATERSHED NUMBER  1


NUMBER OF CELLS =  17242


CURVE NUMBER = 84


AVERAGE EXCESS RAINFALL FOR WATERSHED =   .77


LONGEST FLOWPATH =  8880.21 METERS    SLOPE =   .0199
LENGTH OF MAINSTREAM =  8480.80 METERS    SLOPE =  .0158
TIME OF CONCENTRATION =   602.96 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
          1         398         477         346         227         271
        484         610         575         295         470         548
        857        1062        1386         496         310         622
        796         921        1014        1010         844         428
        353         342         312         295         279         121
         93          97          92          79          54          94
        149         125          73          58          40          31
         20          16           9          10          12          15
         10           5           0           0           0           0
          0           1           2           2           2           1
          1
```

Figure 7-2 Data file for Nine Mile Run

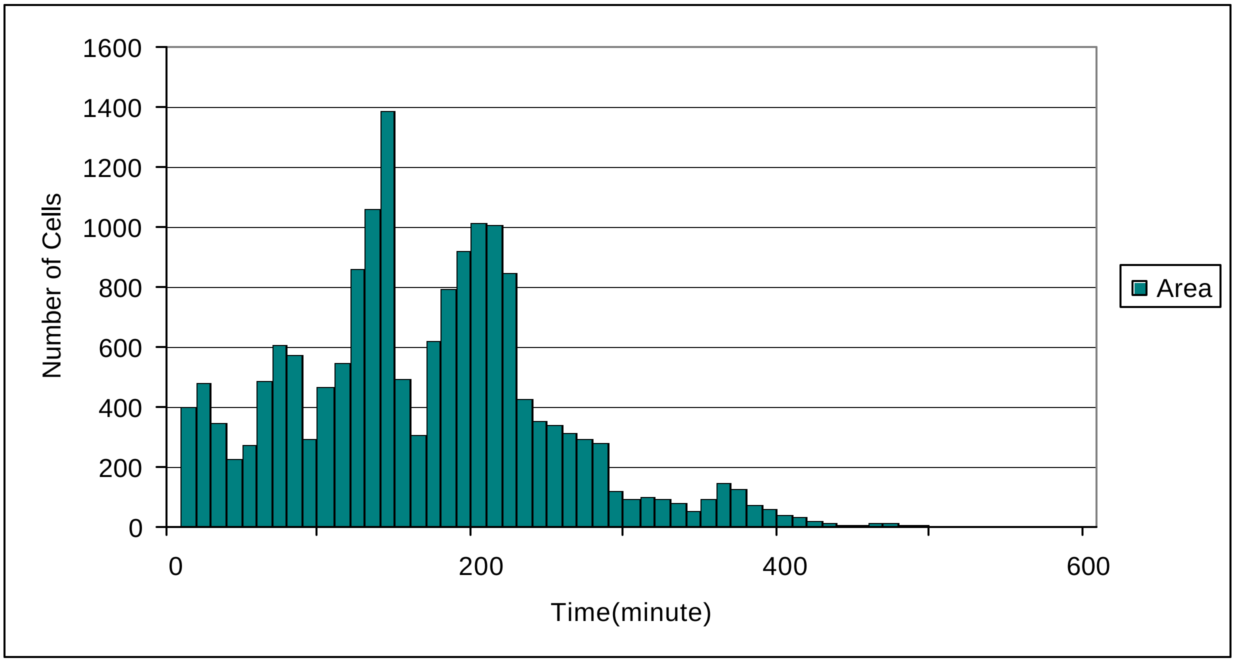

Figure 7-3 Time area histogram for Nine Mile Run

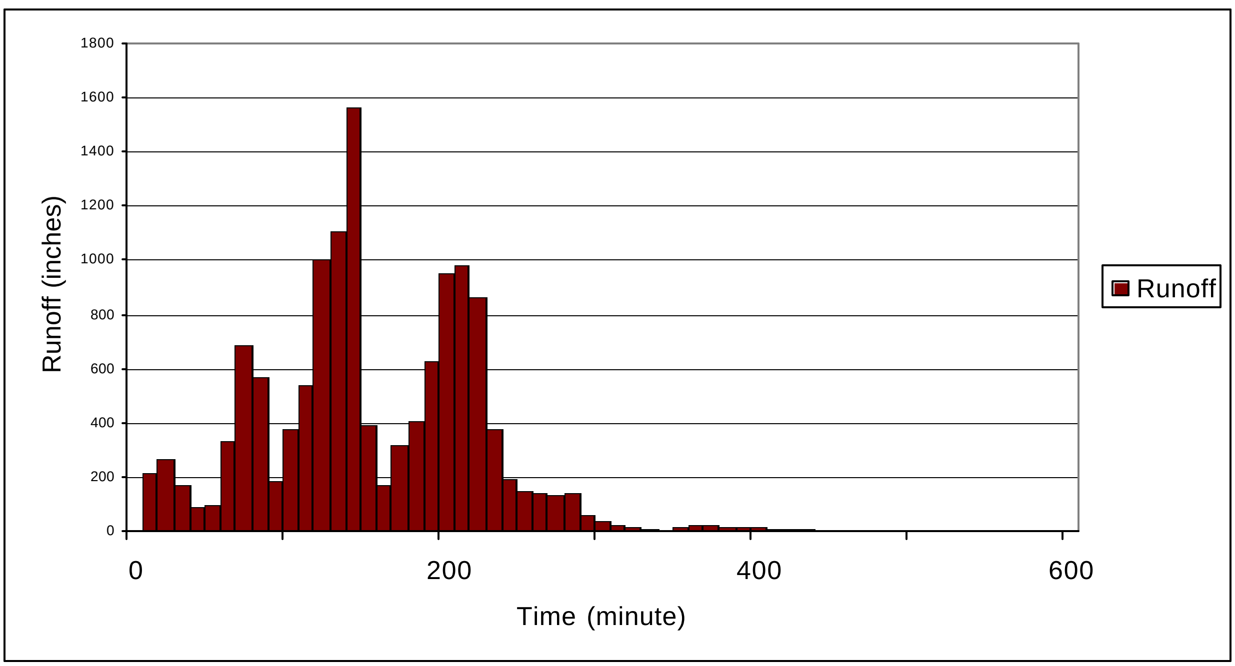

Figure 7-4 Runoff time histogram for Nine Mile Run

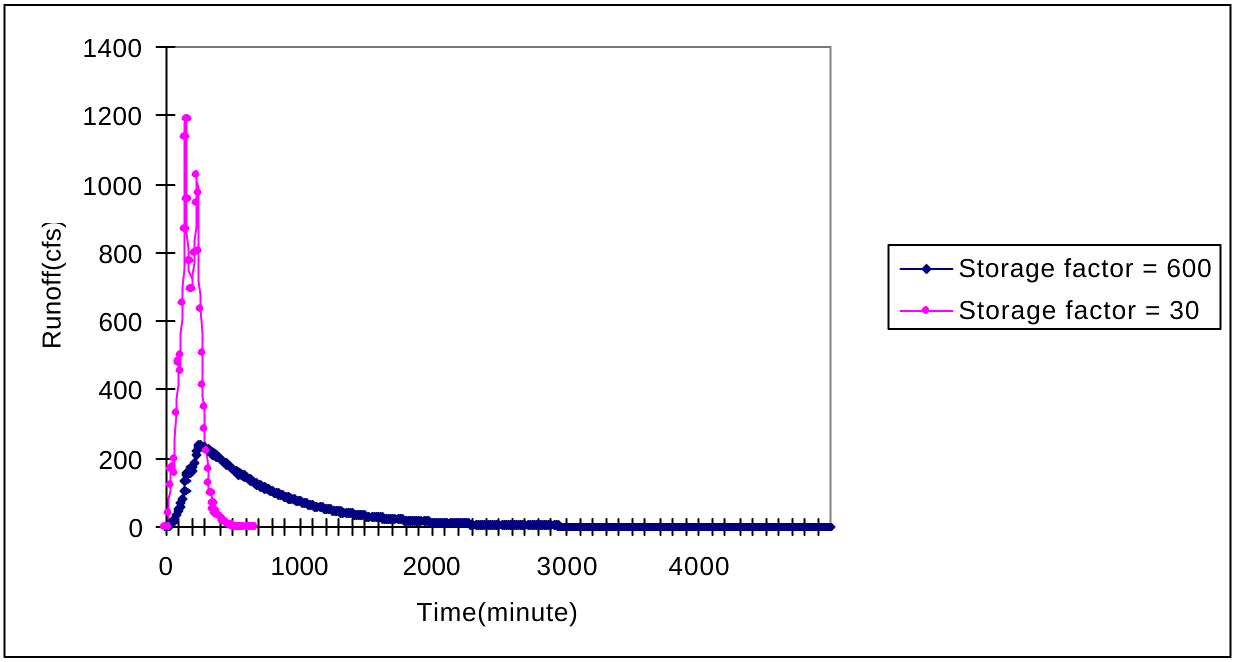

Figure 7-5 Direct Runoff Hydrograph for Nine Mile Run

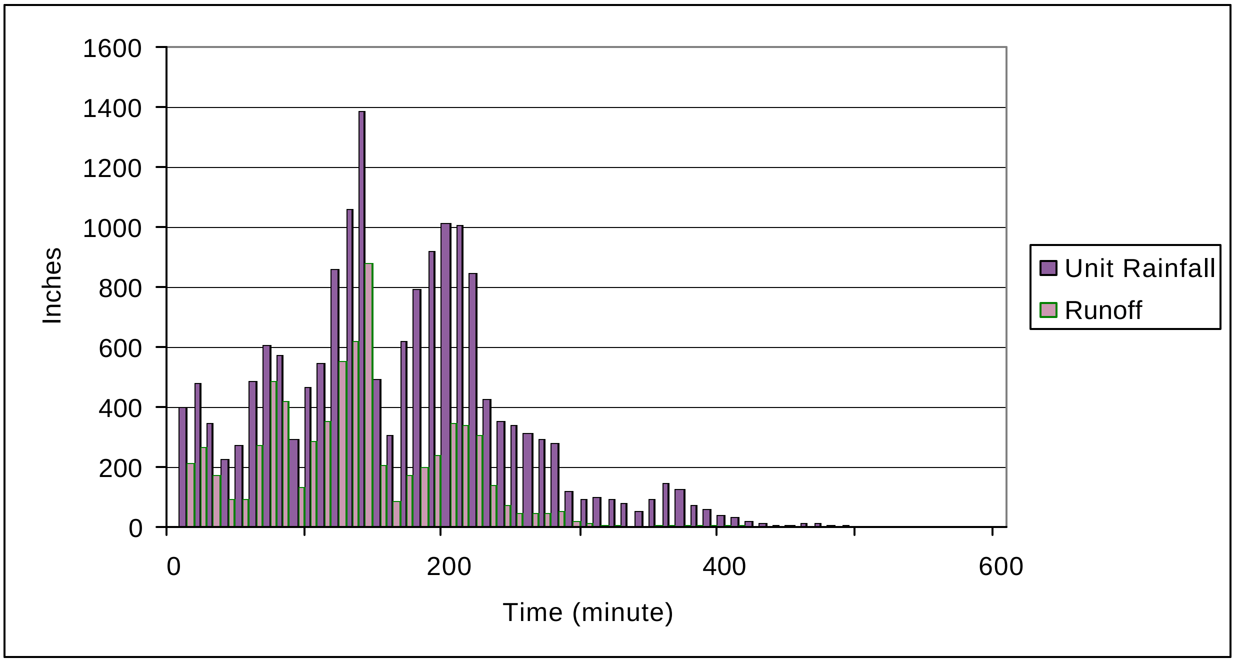

Figure 7-6 Time area and Runoff time histograms for Nine Mile Run with distributed Curve Numbers

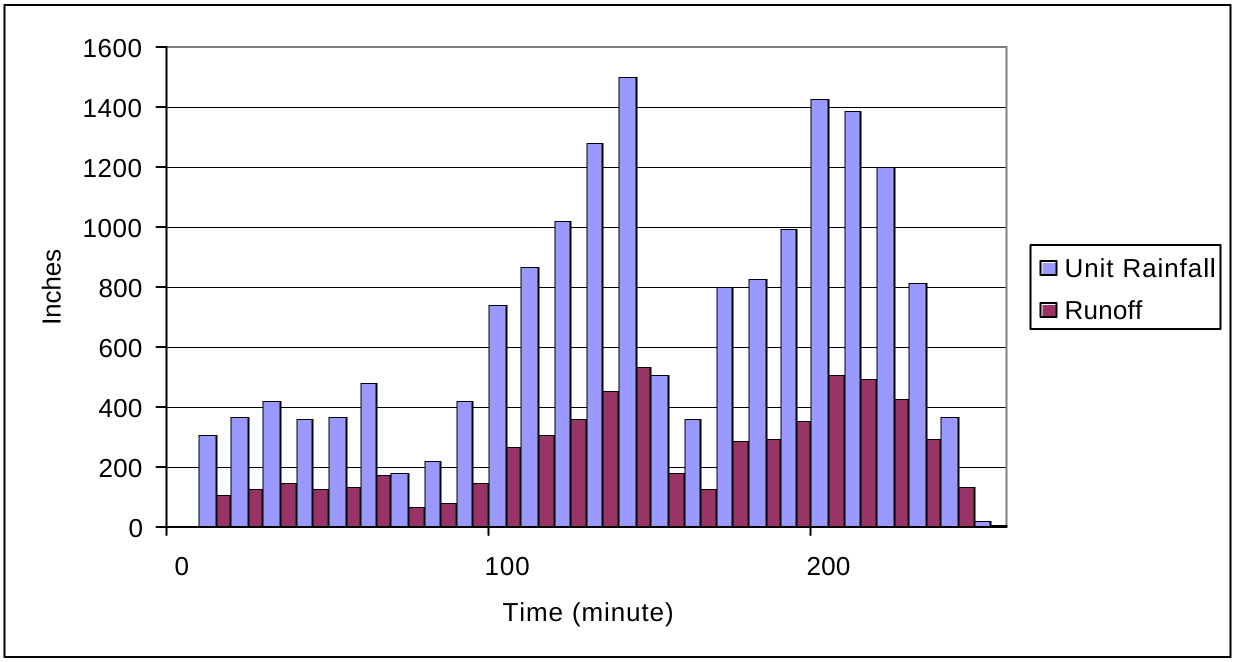

Figure 7-7 Time area and Runoff time histograms for Nine Mile Run with a single Curve Number

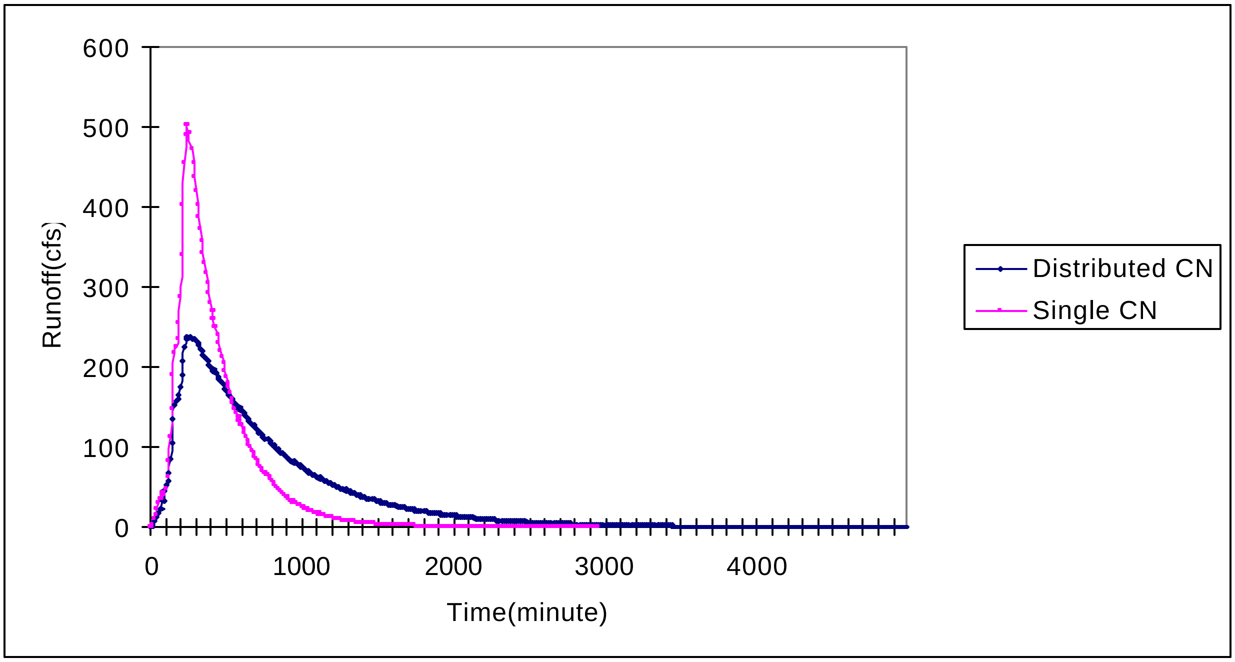

Figure 7-8 Effect of the spatial distribution of Curve Numbers on the DRHs for Nine Mile Run with storage factor equal to travel time

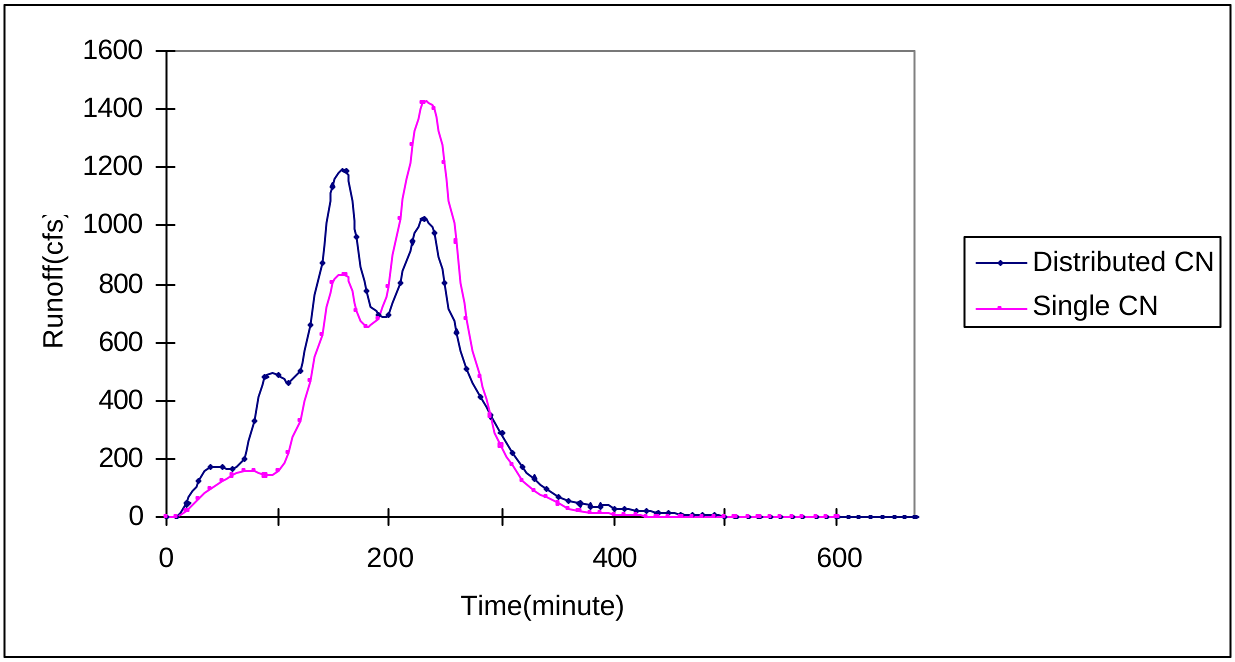

Figure 7-9 Effect of the spatial distribution of Curve Numbers on the DRHs for Nine Mile Run with storage factor equal to 30 minutes

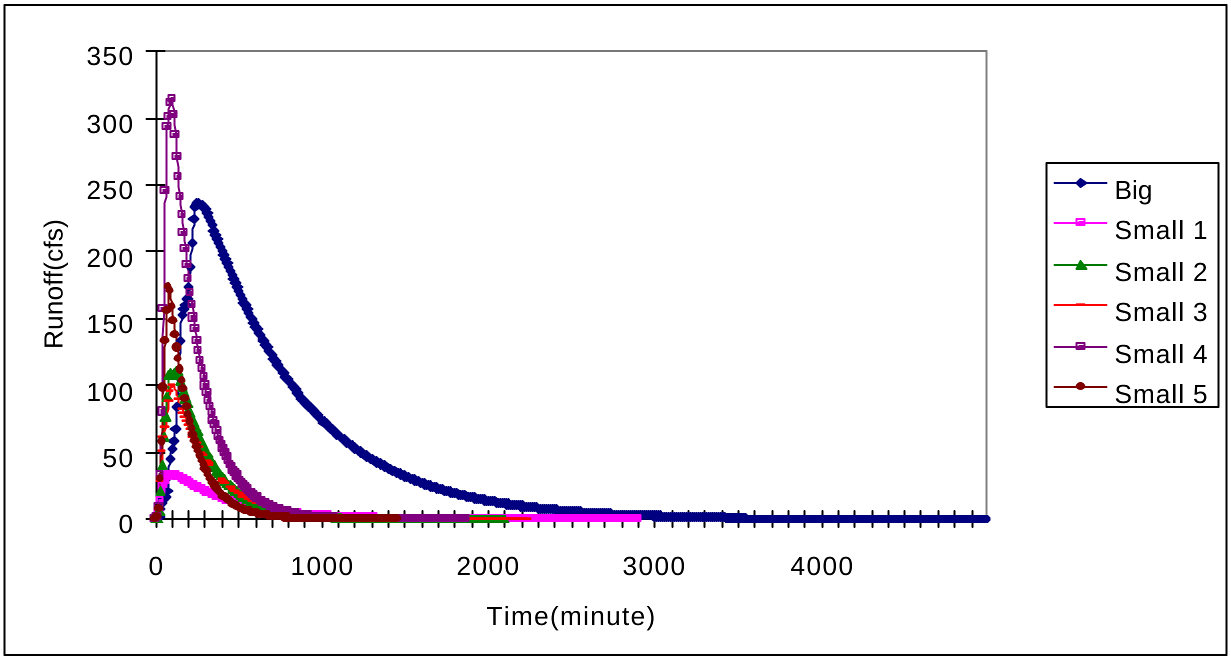

Figure 7-10 10 minute DRHs for the Sub Watersheds and the Whole Nine Mile Run with storage factor equal to time of travel

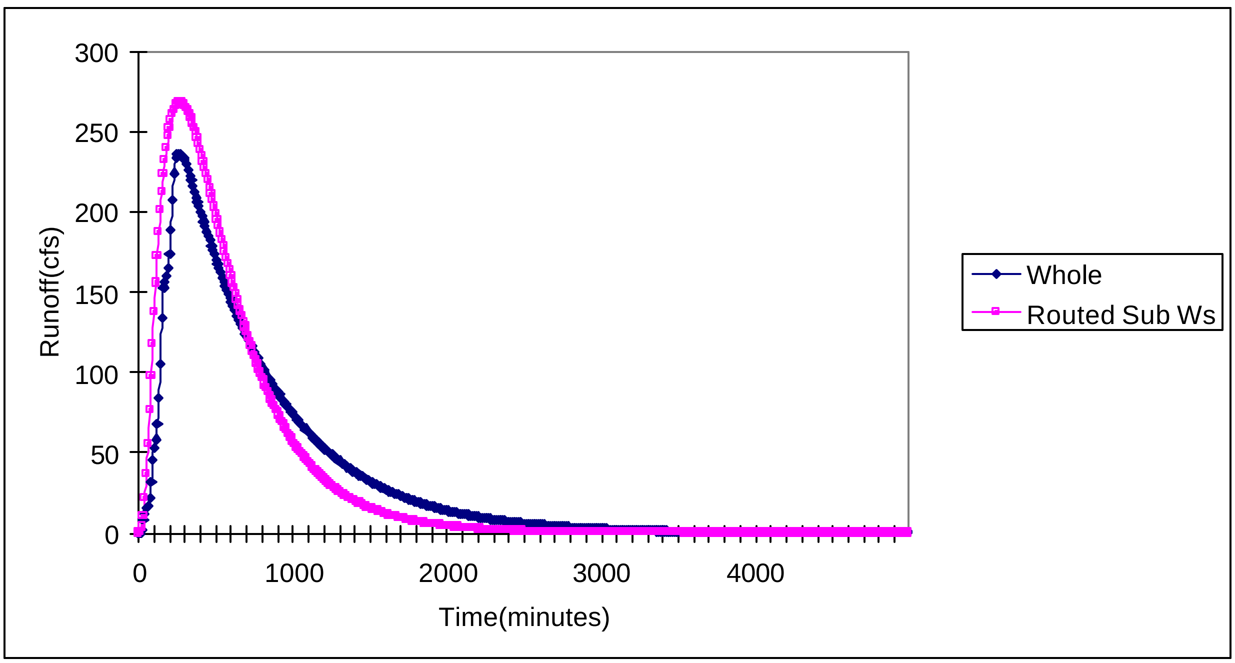

Figure 7-11 10 minute DRHs for the Routed Sub Watersheds and the Whole Nine Mile Run with storage factor equal to time of travel

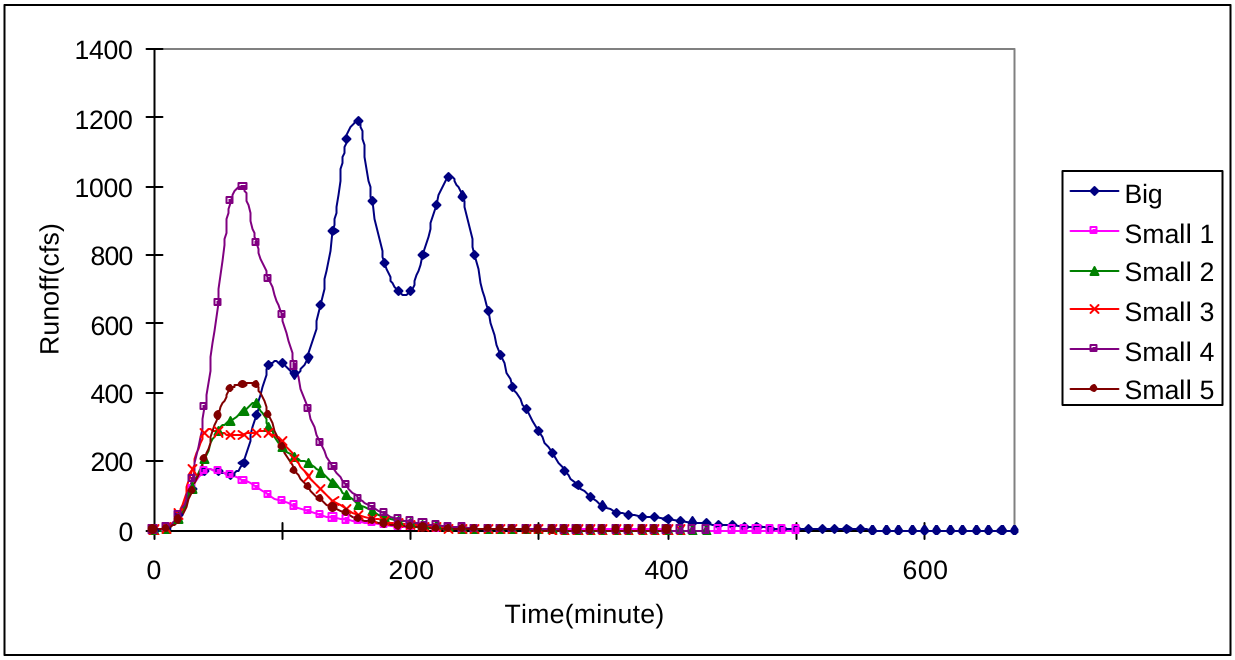

Figure 7-12 10 minute DRHs for the Sub Watersheds and the Whole Nine Mile Run with storage factor of 30 minutes

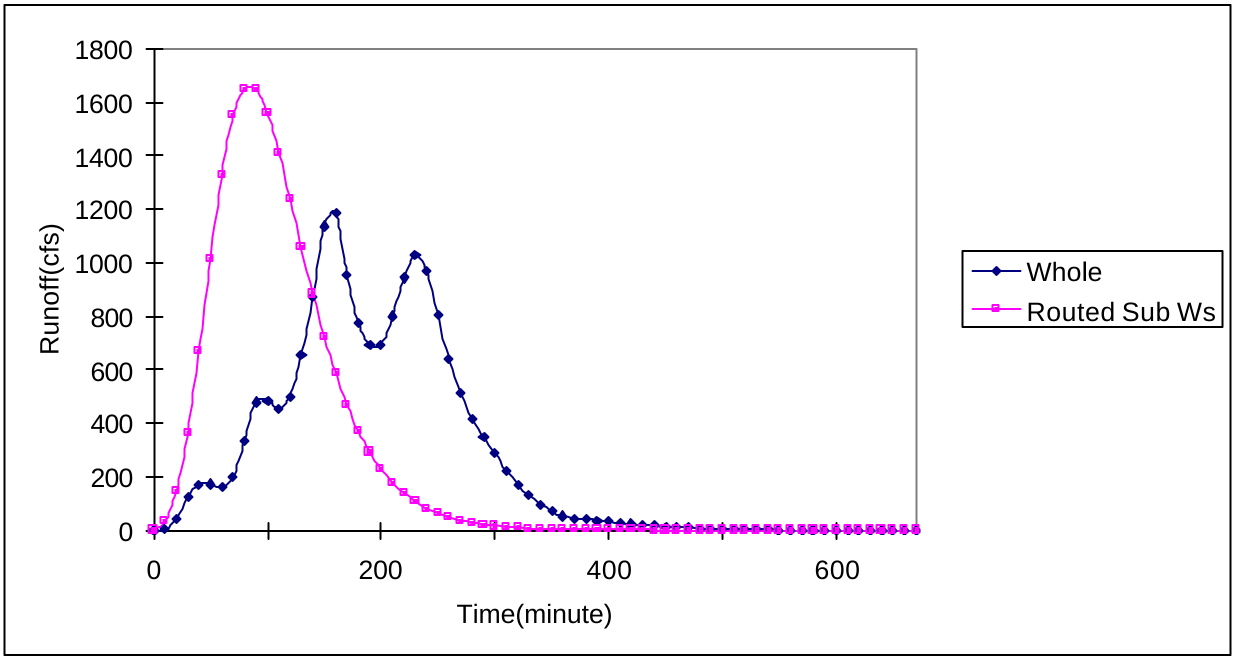

Figure 7-13 10 minute DRHs for the Routed Sub Watersheds and the Whole Nine Mile Run with storage factor of 30 minutes

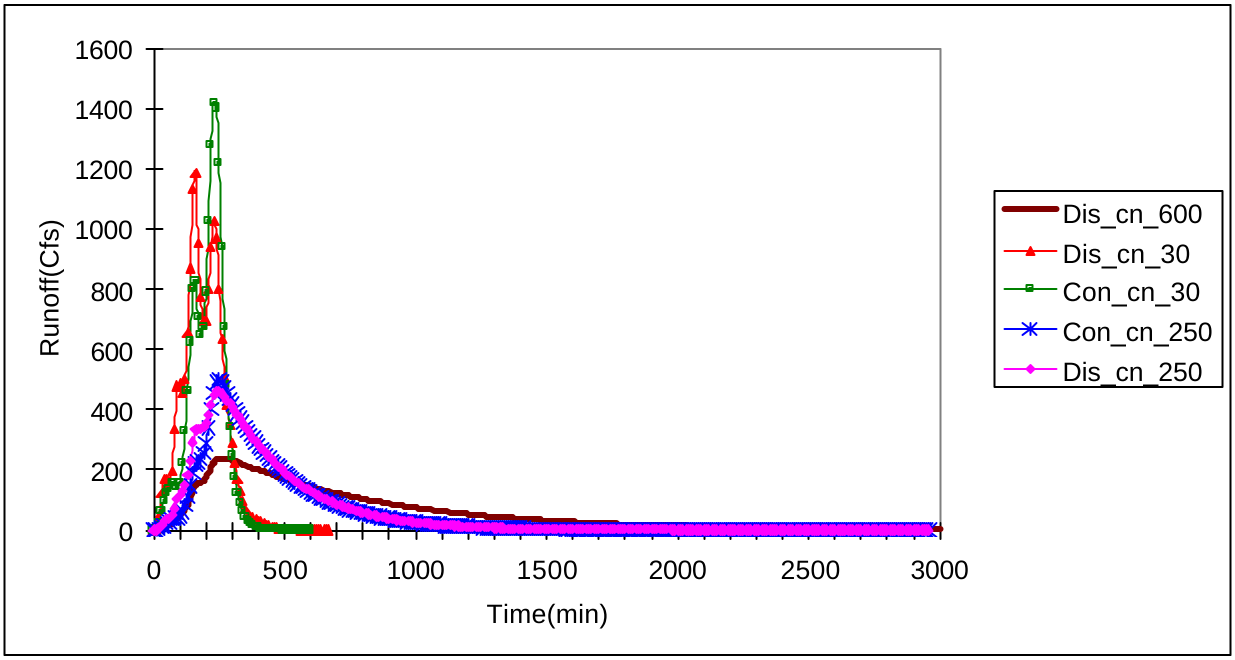

Figure 7-14 Effect of distribution of Curve Numbers and Storage factor on the 10 minute DRHs for Nine Mile Run with Distributed Precipitation

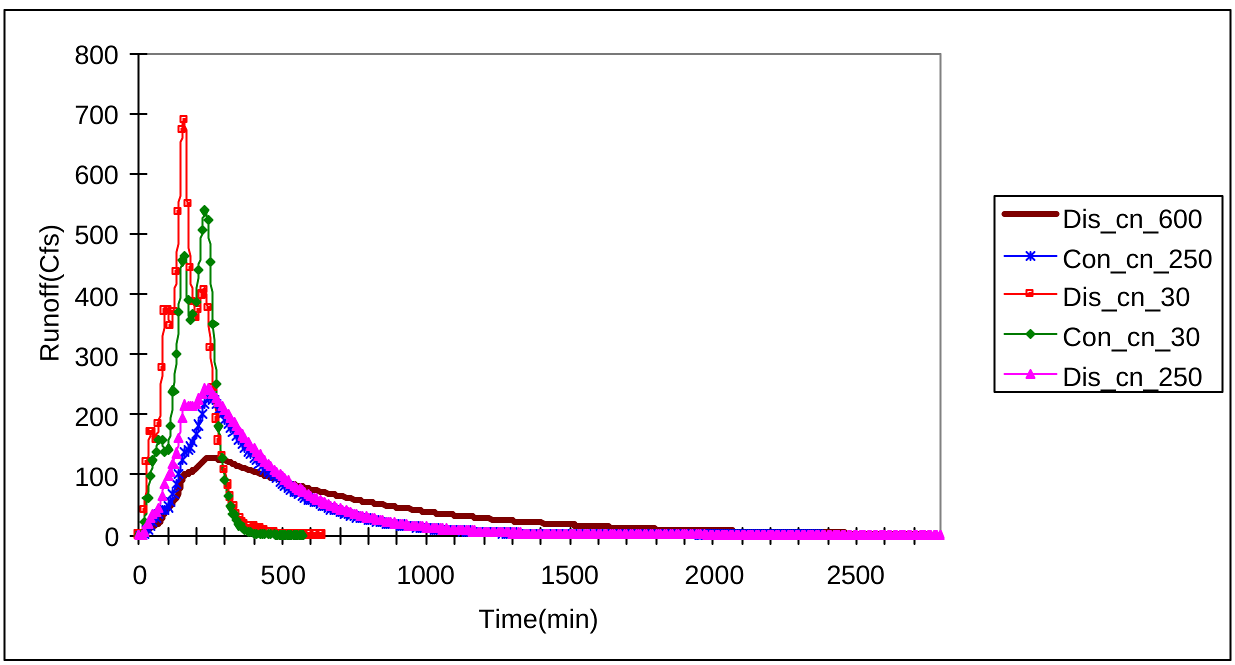

Figure 7-15 Effect of distribution of Curve Numbers and Storage factor on the 10 minute DRHs for Nine Mile Run with Unit Precipitation

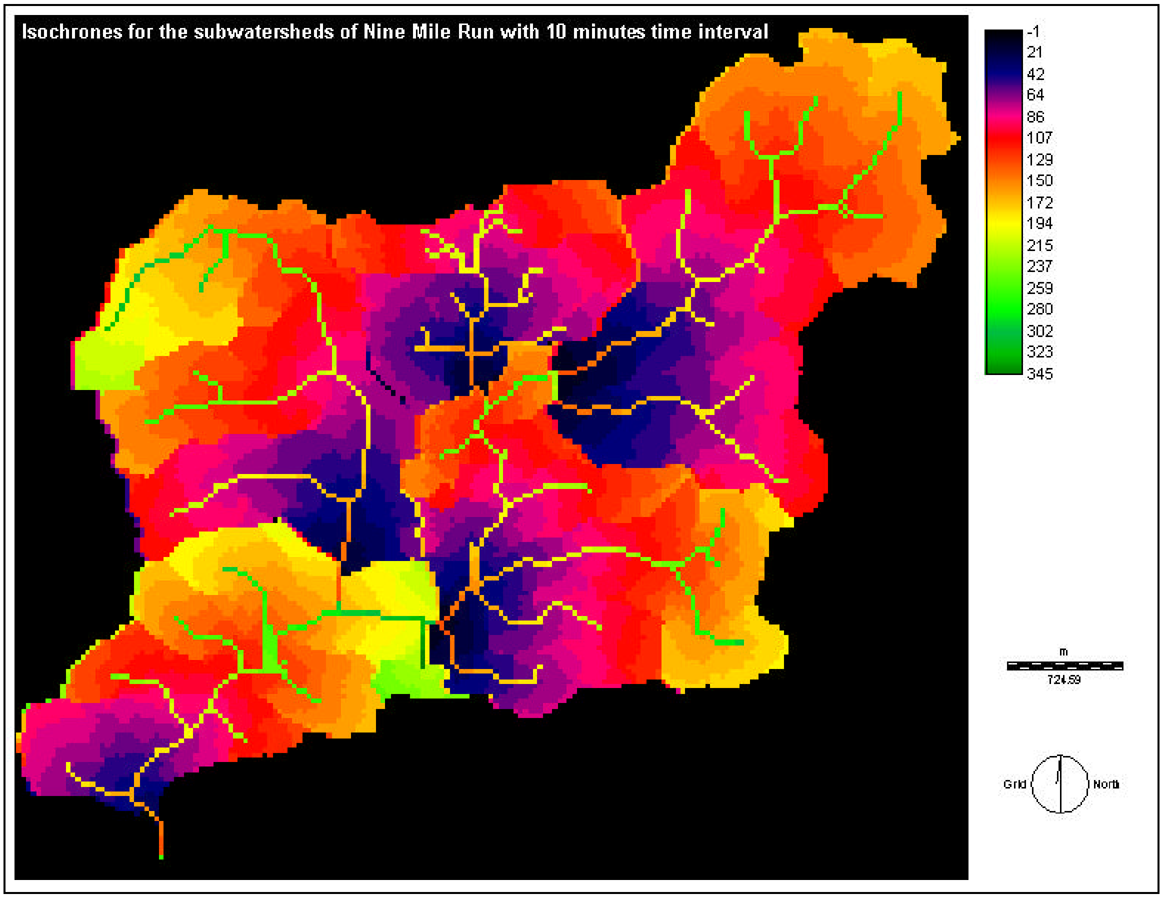

Figure 7-16 Isochrones with 10 minute time interval for the individual sub watersheds of Nine Mile Run

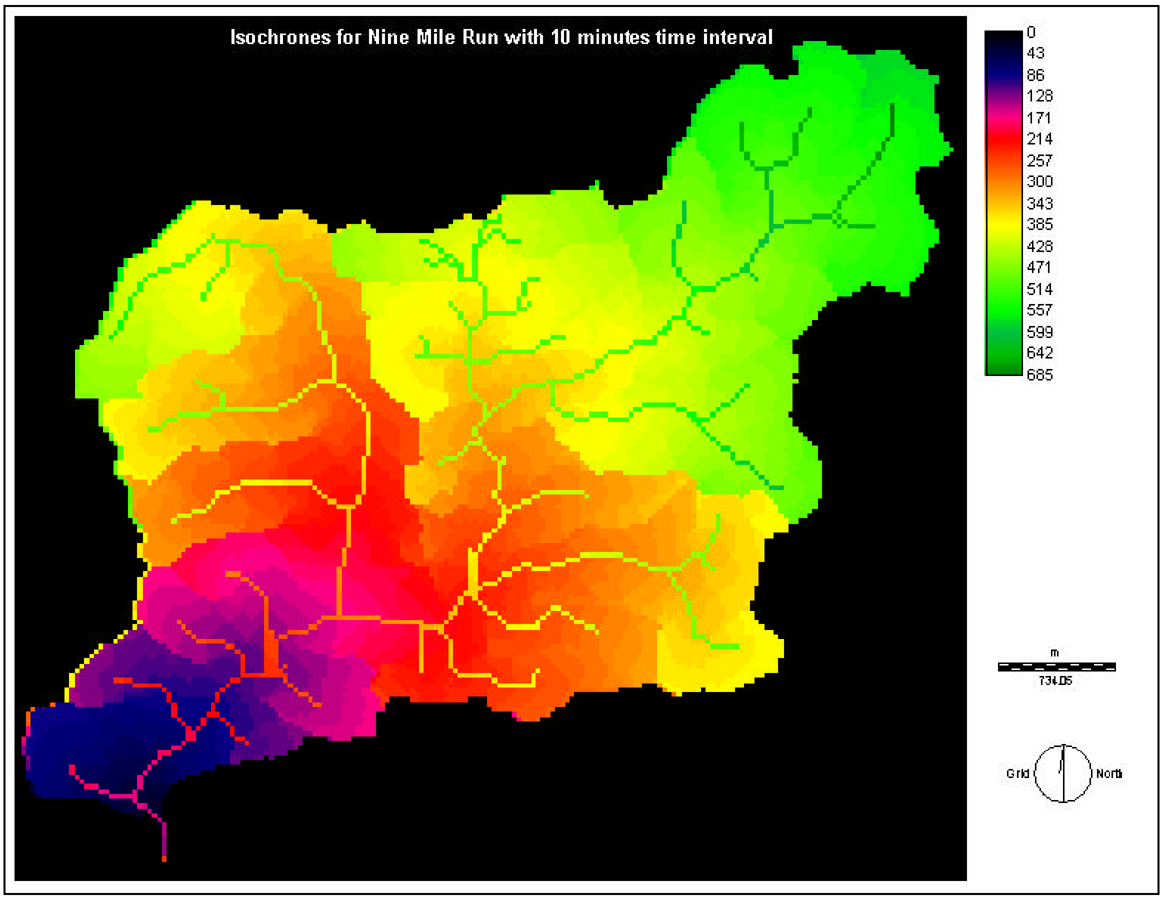

Figure 7-17 Isochrones with 10 minute time interval for the whole Nine Mile Run

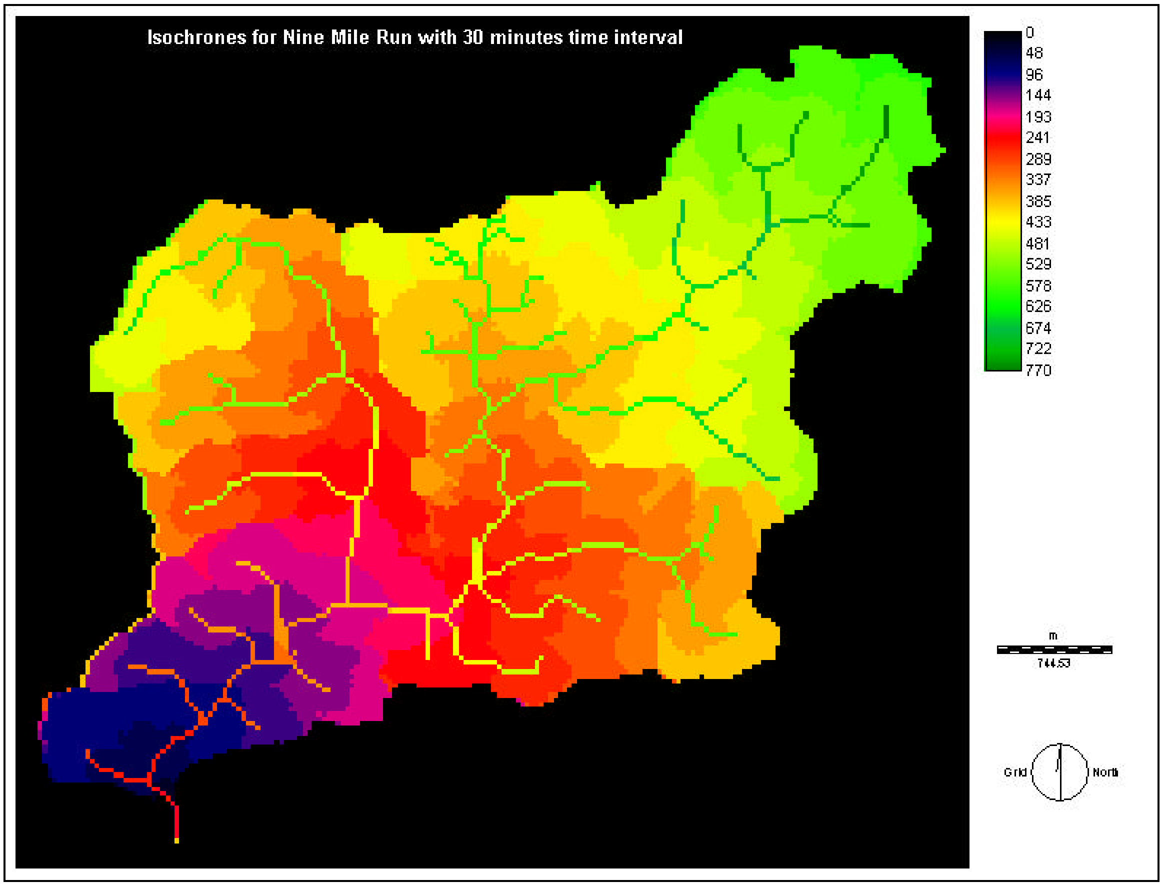

Figure 7-18 Isochrones with 30 minute time interval for the whole Nine Mile Run

7.2 Results for the Thompson Run watershed

```
THE CURVE-NUMBER CALCULATION FILE
---------------------------------


WATERSHED NUMBER:  1


NUMBER OF CELLS IN THE WATERSHED:     45456



CURVE NUMBER                        NUMBER OF CELLS
------------                        ---------------
     45                                  6188
     55                                  4680
     66                                  1273
     68                                  3588
     77                                   139
     85                                   746
     86                                  9043
     89                                  2313
     90                                  4069
     92                                 11939
     94                                  1478


        CURVE NUMBER FOR THE WATERSHED: 78
```

Figure 7-19 Curve Number file for Thompson Run

```
WATERSHED NUMBER  1


NUMBER OF CELLS =  45455


CURVE NUMBER = 78


AVERAGE EXCESS RAINFALL FOR WATERSHED =   .70


LONGEST FLOWPATH = 12171.18 METERS    SLOPE =   .0140
LENGTH OF MAINSTREAM = 11277.21 METERS    SLOPE =  .0090
TIME OF CONCENTRATION =  1519.17 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
          0           0           3         106         282         326
        143         318         718         763         868        1293
       1161         951         947         957        1069        1394
       1581        1278        1504        1064        1248        1201
       1056         837         803         803         858        1081
       1099         748         675         711         951         944
        878         737         622         414         207         100
         70          64          59          70          93          82
         44          76         124          68          65          80
         59          32          72          96         100          88
        104         122         133         137         163         218
        241         300         352         335         297         337
        300         325         333         294         246         237
        207         160         154         164         118         141
        144         158         165         159         138         147
        153         137         174         149         164         171
        158         159         130         116         116         141
        140         148         111          95          94          94
         89          86          72          78          85          94
         79          80          71          88          93          94
         96          79          64          78          80          78
         69          56          42          45          42          51
         48          55          49          40          48          40
         51          54          45          52          43          49
         43          41          50          43          45          27
         14           8
```

Figure 7-20 Data file for Thompson Run

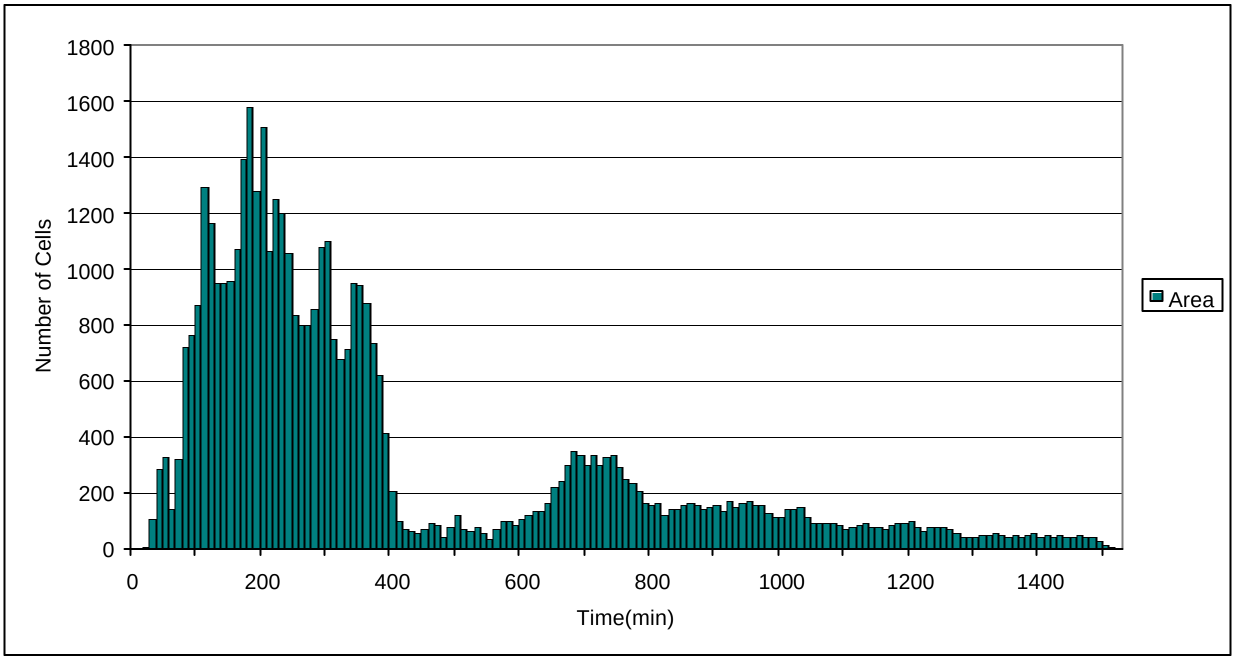

Figure 7-21 Time area histogram for Thompson Run

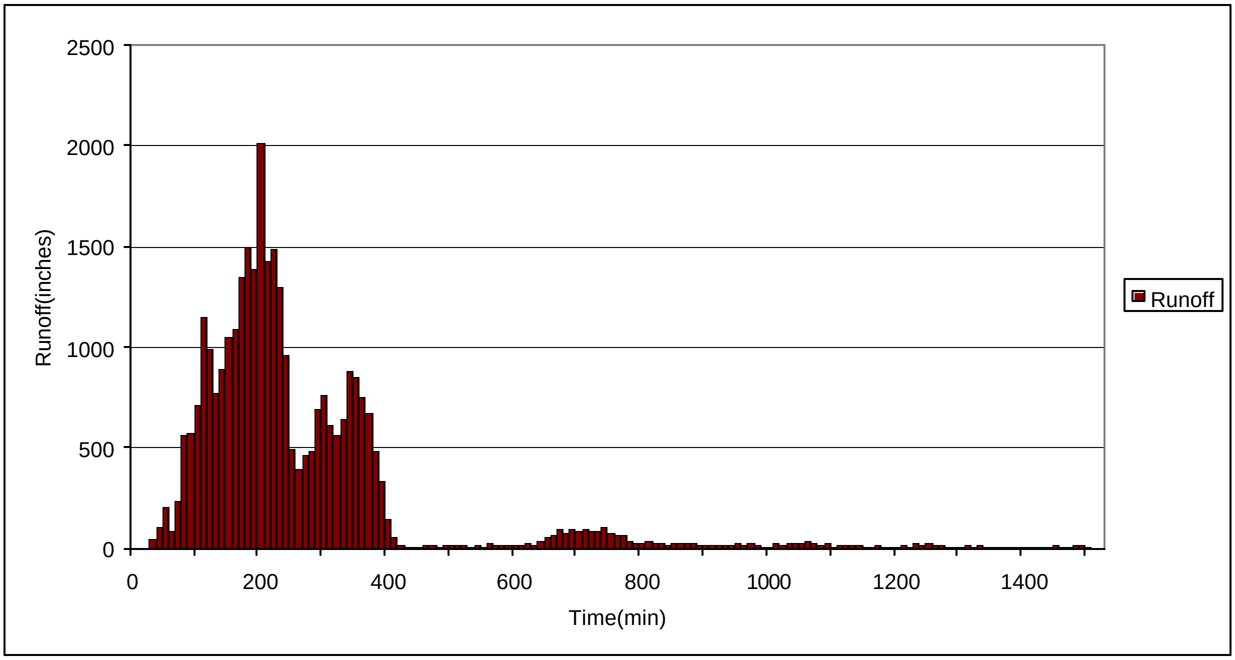

Figure 7-22 Runoff time histogram for Thompson Run

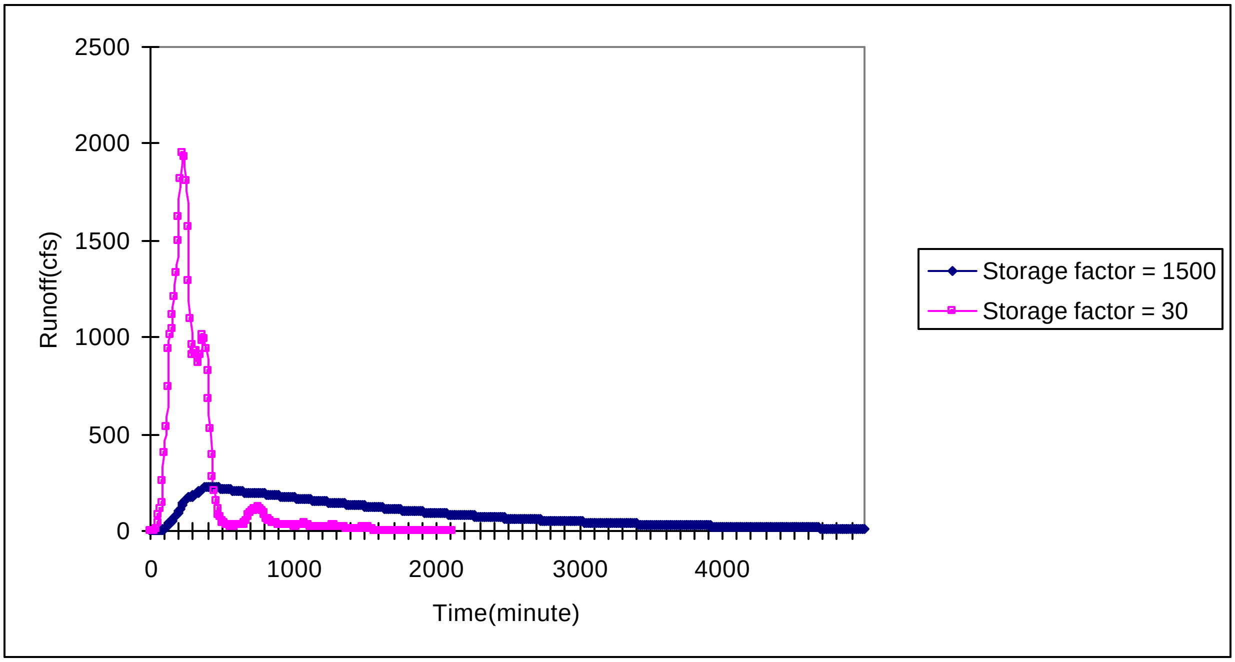

Figure 7-23 Direct Runoff Hydrograph for Thompson Run

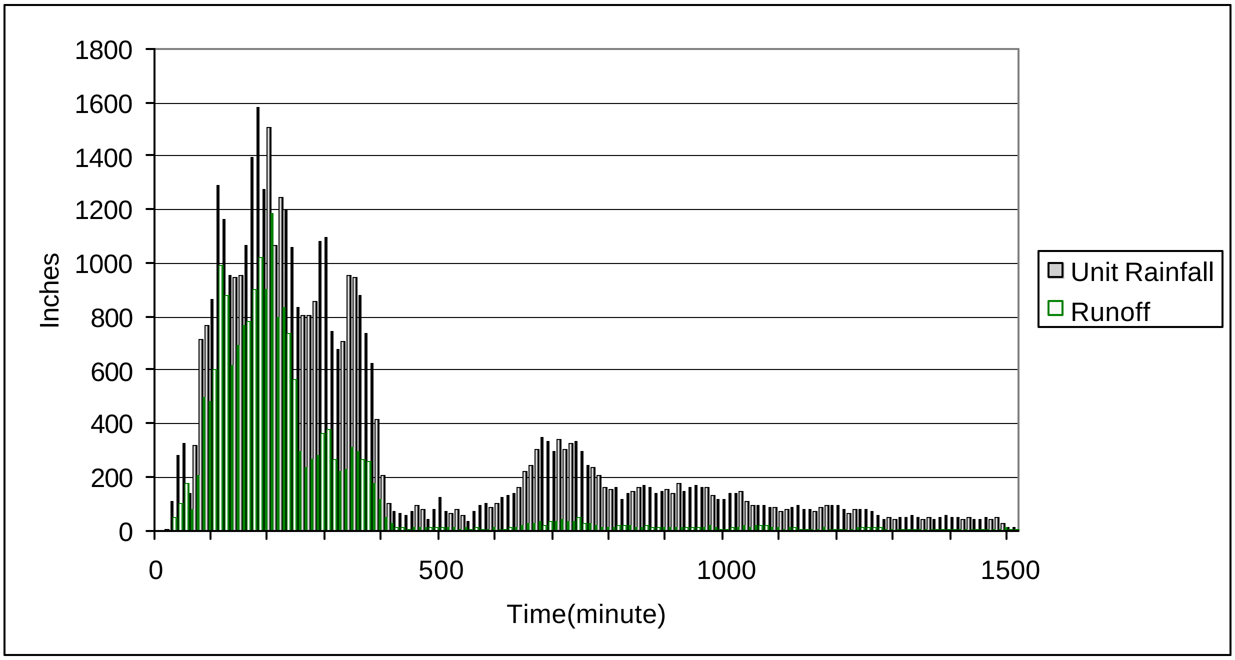

Figure 7-24 Time area and Runoff time histograms for Thompson Run with distributed Curve Numbers

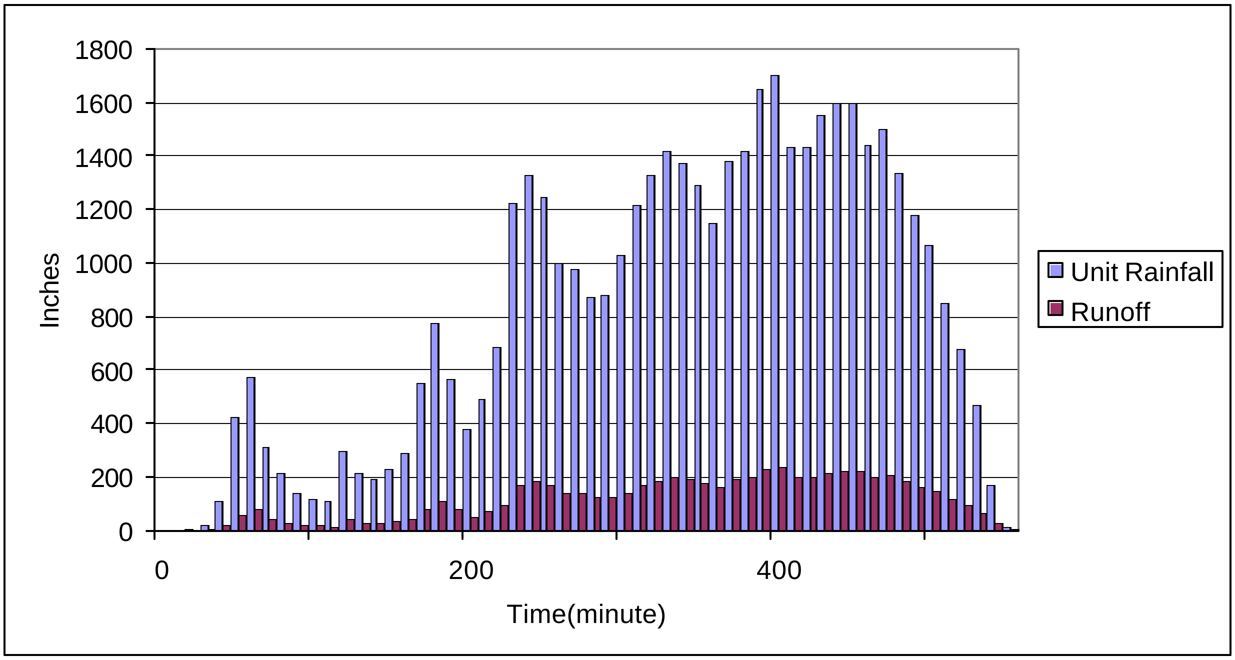

Figure 7-25 Time area and Runoff time histograms for Thompson Run with a single Curve Number

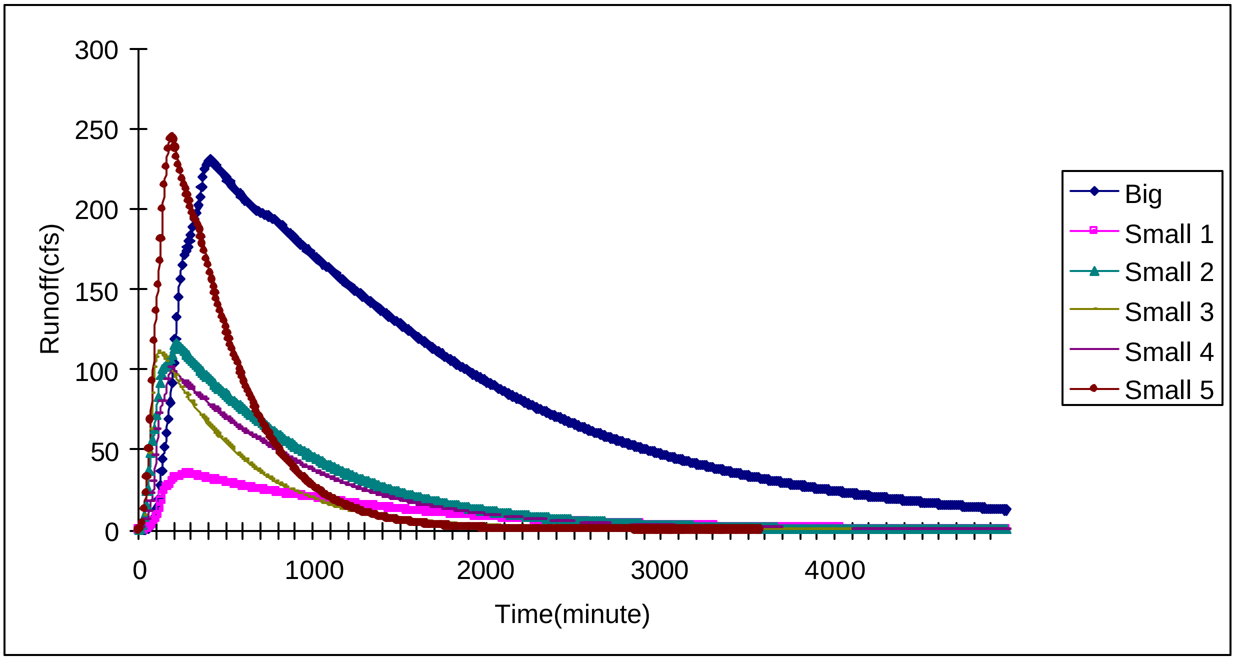

Figure 7-26 10 minute DRHs for the Sub Watersheds and the Whole Thompson Run with storage factor equal to the time of travel

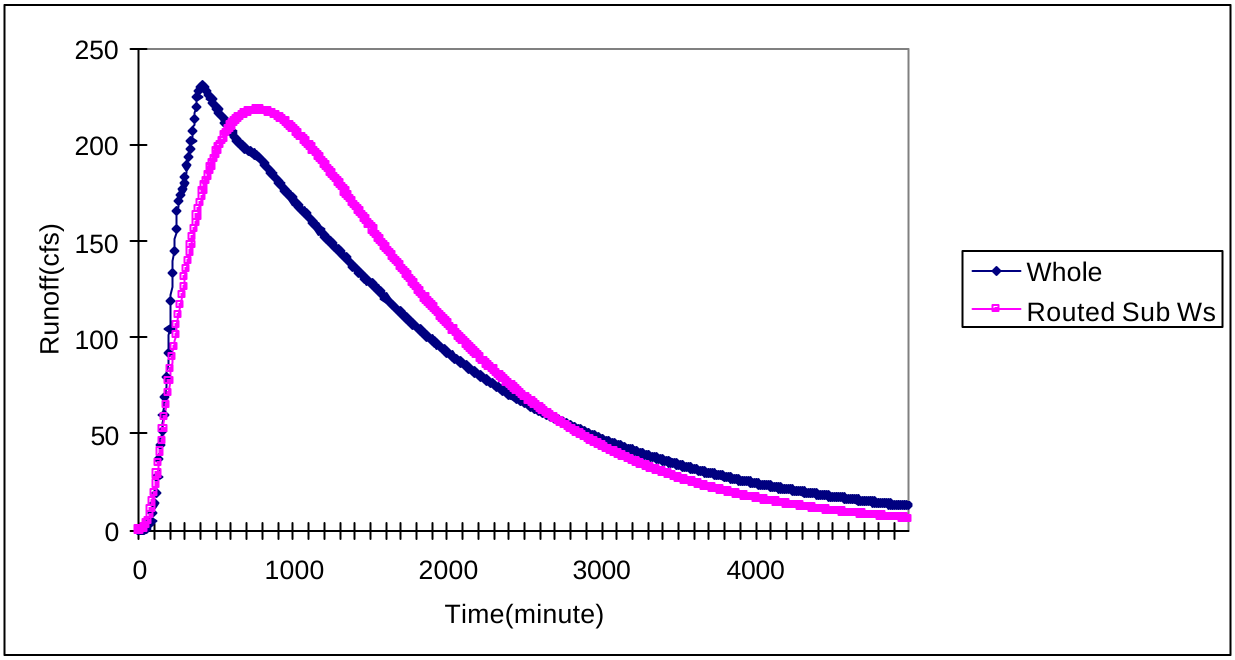

Figure 7-27 10 minute DRHs for the Routed Sub Watersheds and the Whole Thompson Run with the storage factor equal to the time of travel

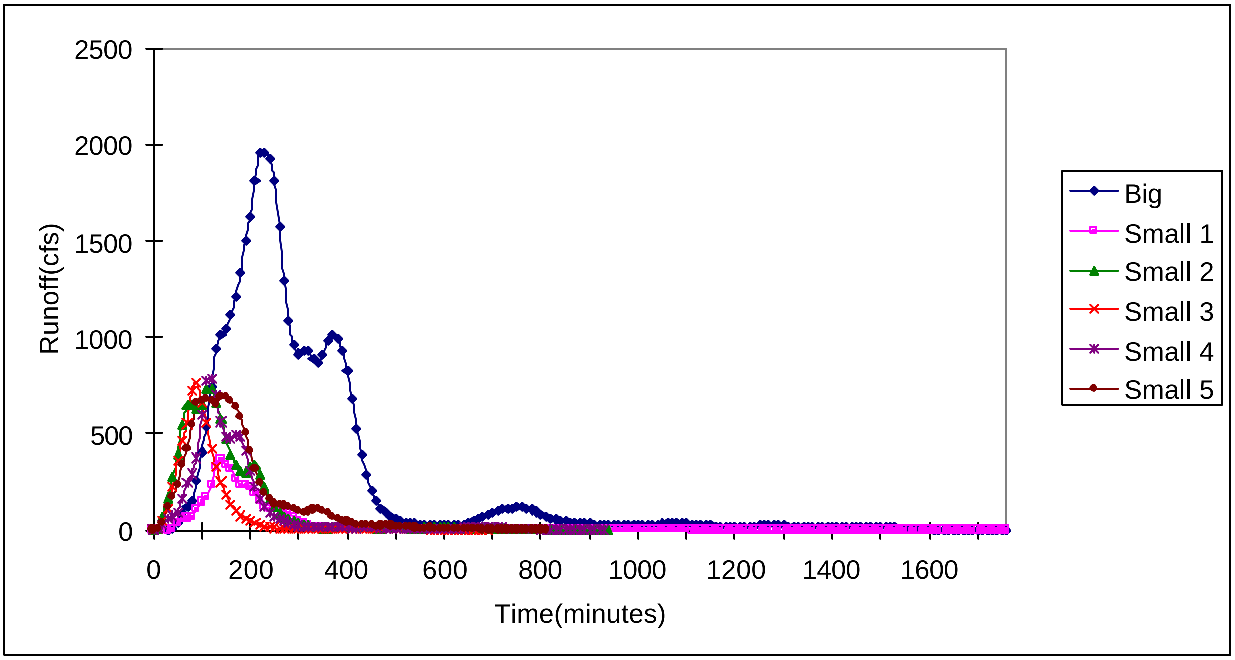

Figure 7-28 10 minute DRHs for the Sub Watersheds and the Whole Thompson Run with storage factor of 30 minutes

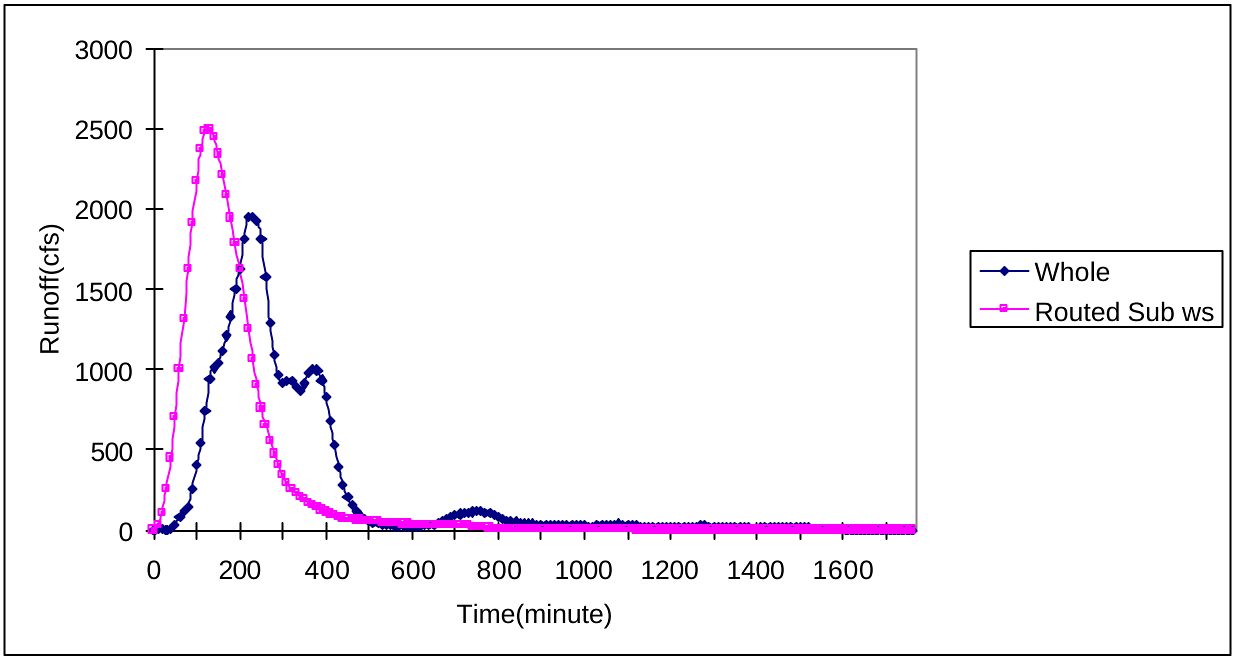

Figure 7-29 10 minute DRHs for the Routed Sub Watersheds and the Whole Thompson Run with the storage factor of 30 minutes

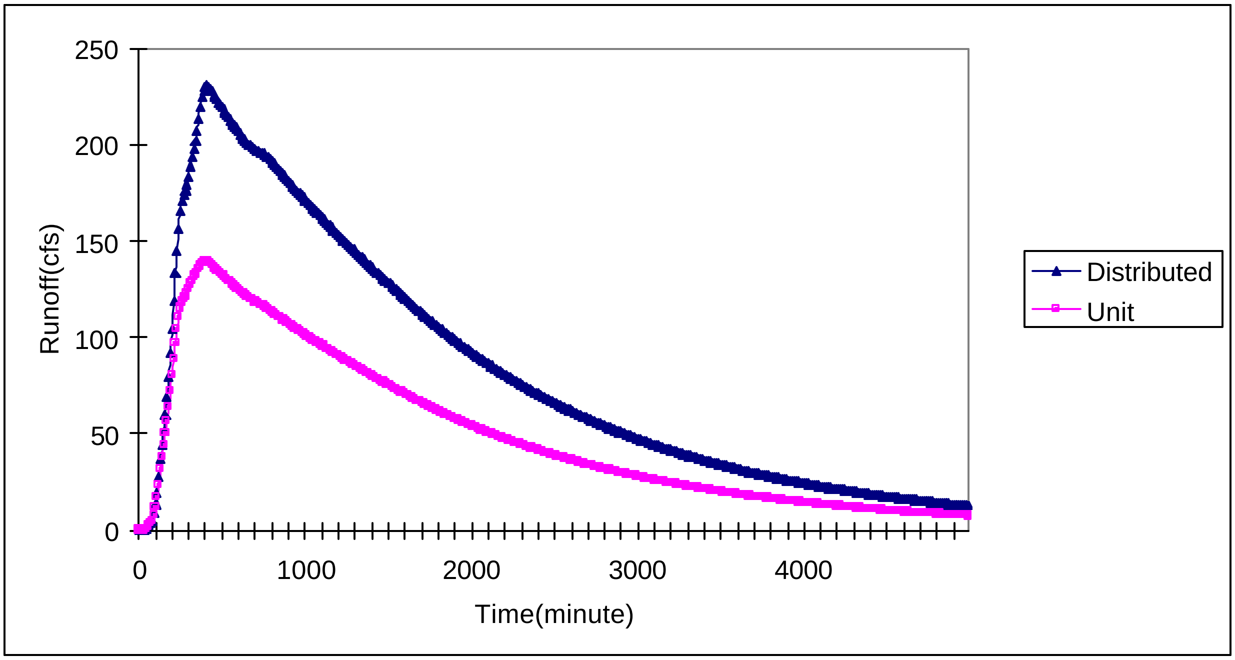

Figure 7-30 10 minute DRHs for Thompson Run with Distributed Curve Numbers, Distributed and Unit Precipitation and storage factor of 1500 minutes

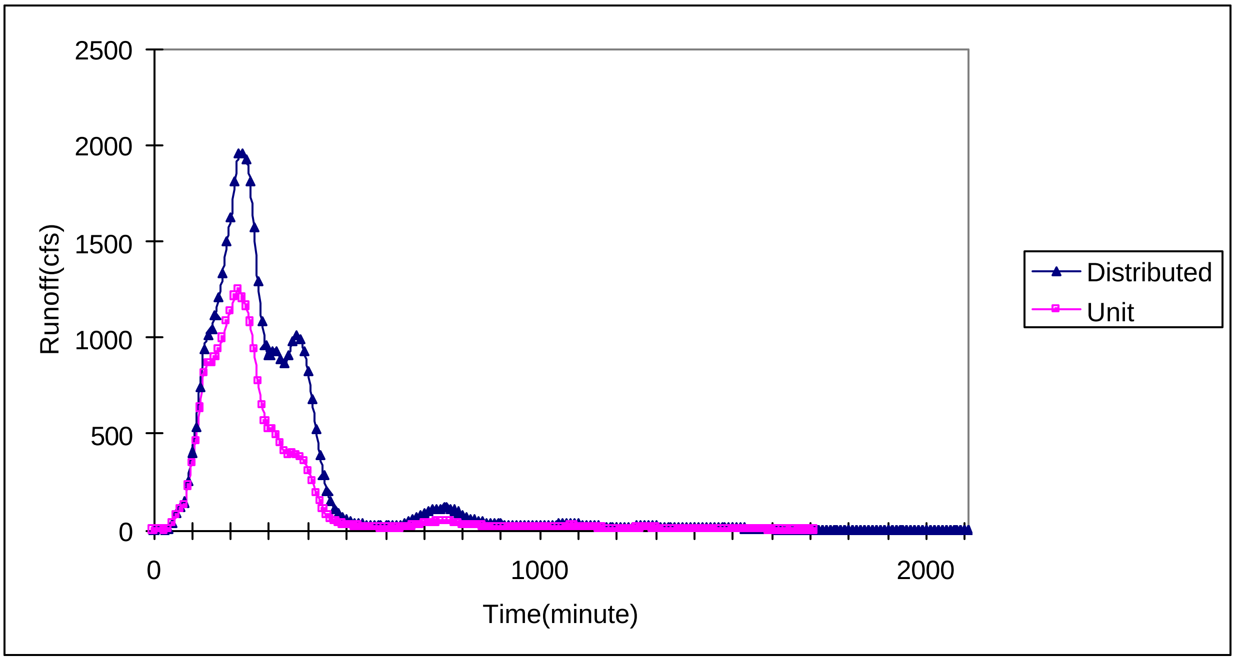

Figure 7-31 10 minute DRHs for Thompson Run with Distributed Curve Numbers Distributed and Unit Precipitation and storage factor of 30 minutes

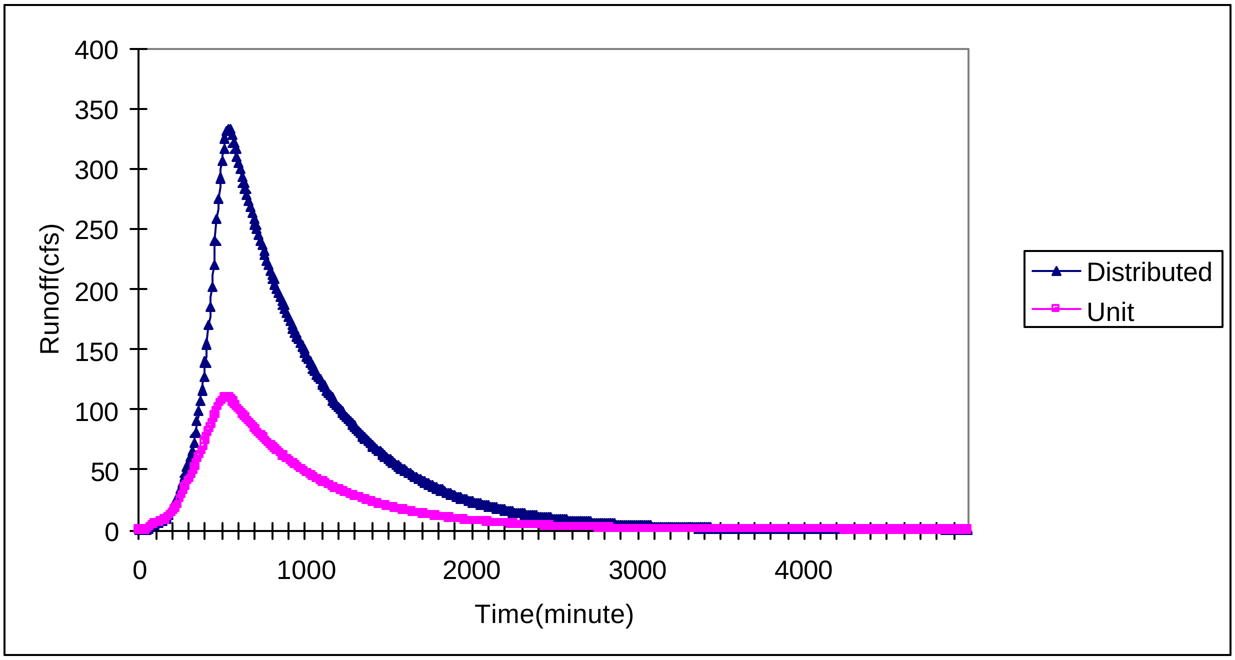

Figure 7-32 10 minute DRHs for Thompson Run with a Single Curve Number, Distributed and Unit Precipitation and storage factor of 1500 minutes

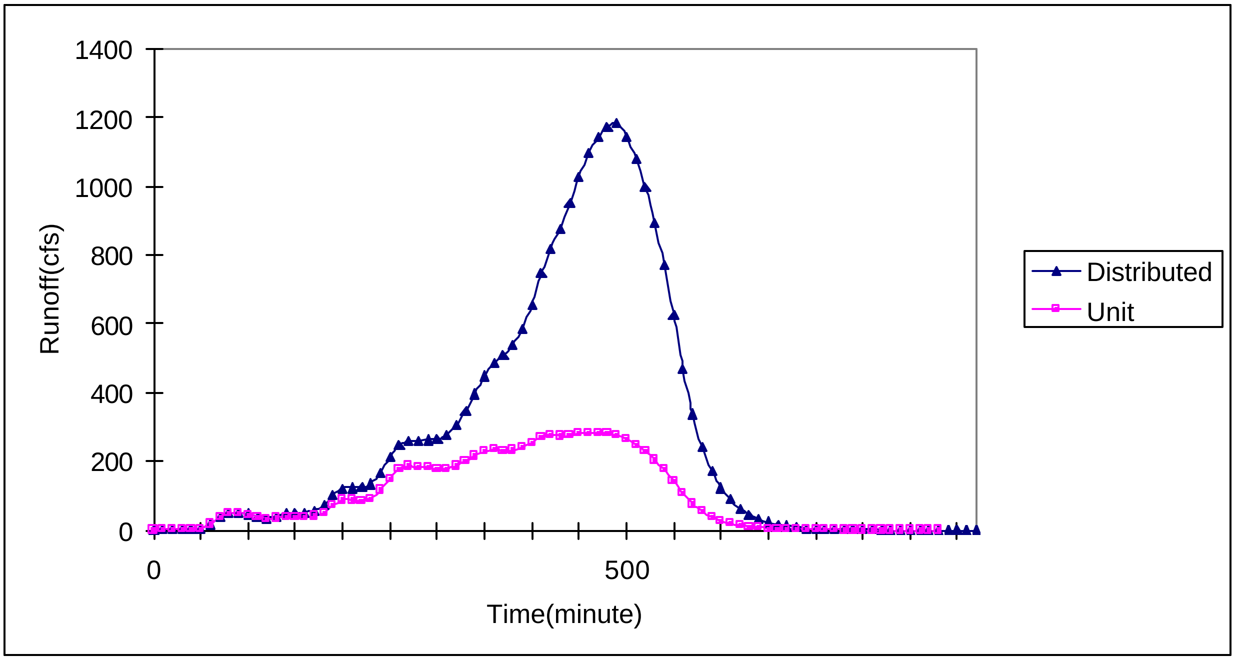

Figure 7-33 10 minute DRHs for Thompson Run with a Single Curve Number, Distributed and Unit Precipitation and Storage Factor of 30 minutes

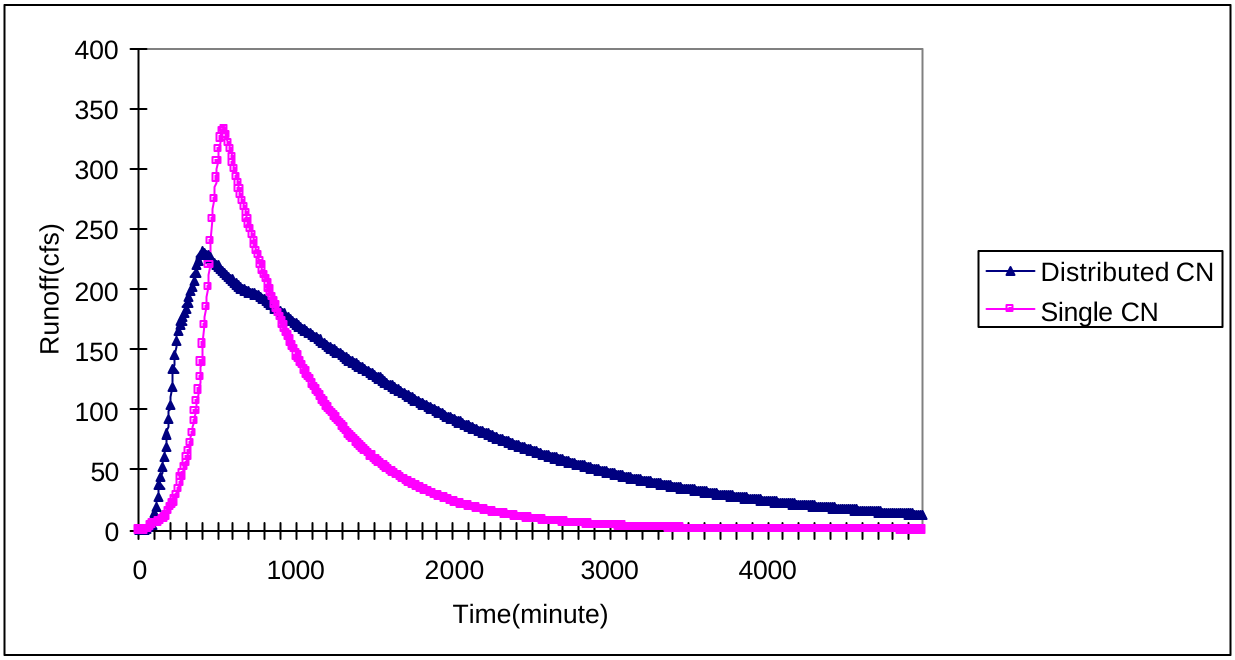

Figure 7-34 10 minute DRHs for Thompson Run with Distributed Precipitation and Single and Distributed Curve Numbers

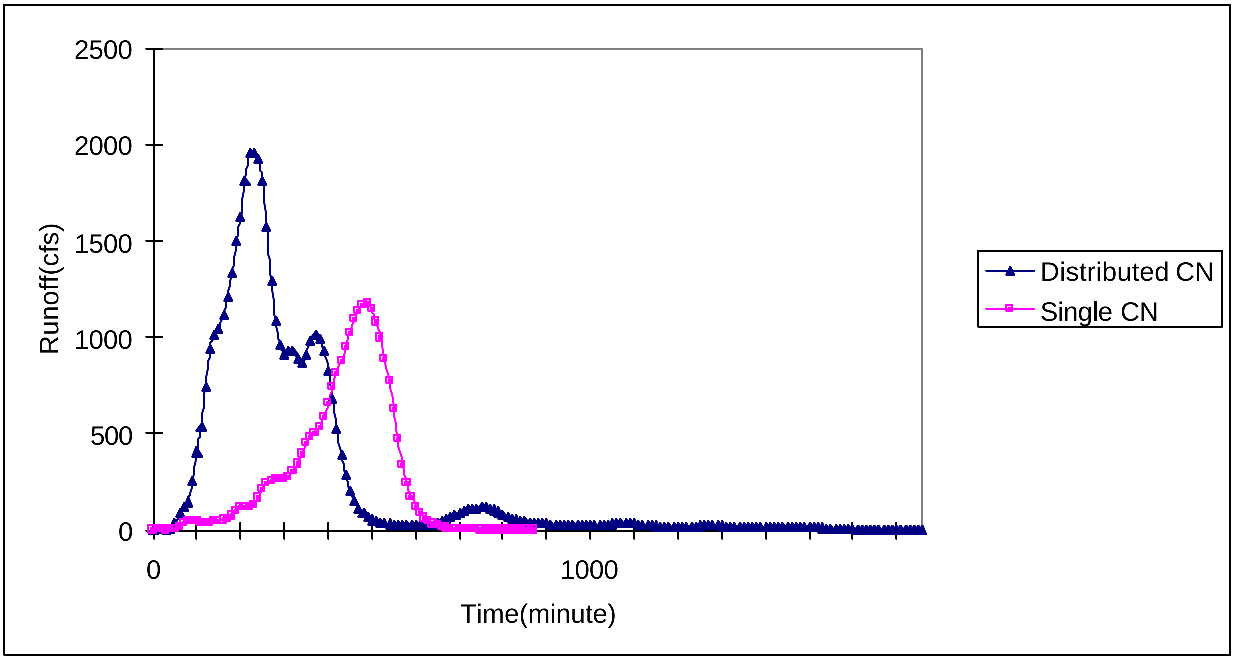

Figure 7-35 10 minute DRHs for Thompson Run with Distributed Precipitation and Distributed and Single Curve Numbers and storage factor of 30 minutes

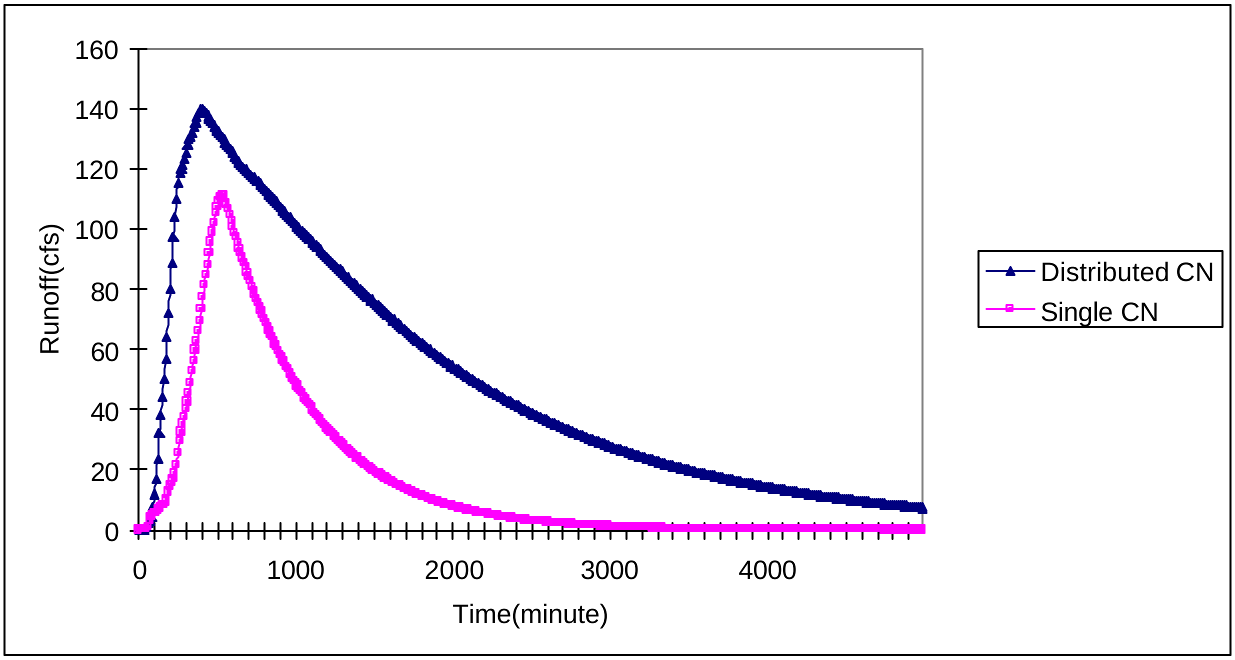

Figure 7-36 10 minute DRHs for Thompson Run with Unit Precipitation and Single and Distributed Curve Numbers

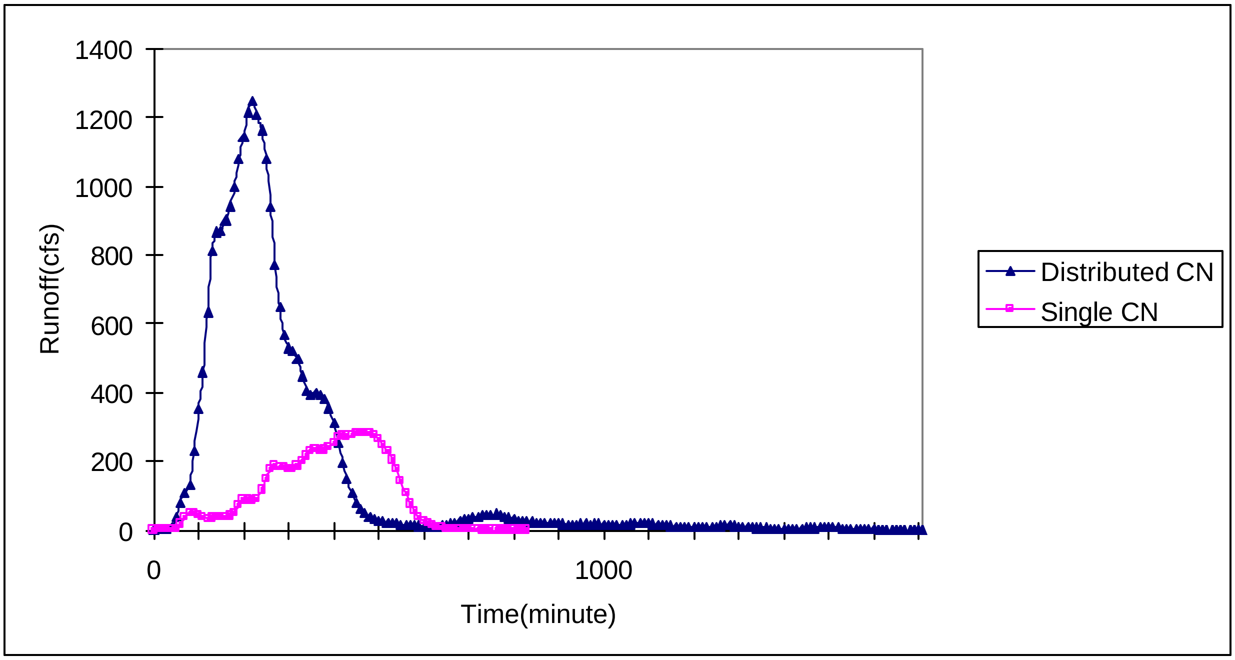

Figure 7-37 10 minute DRHs for Thompson Run with Unit Precipitation and Single and Distributed Curve Numbers and storage factor of 30 minutes

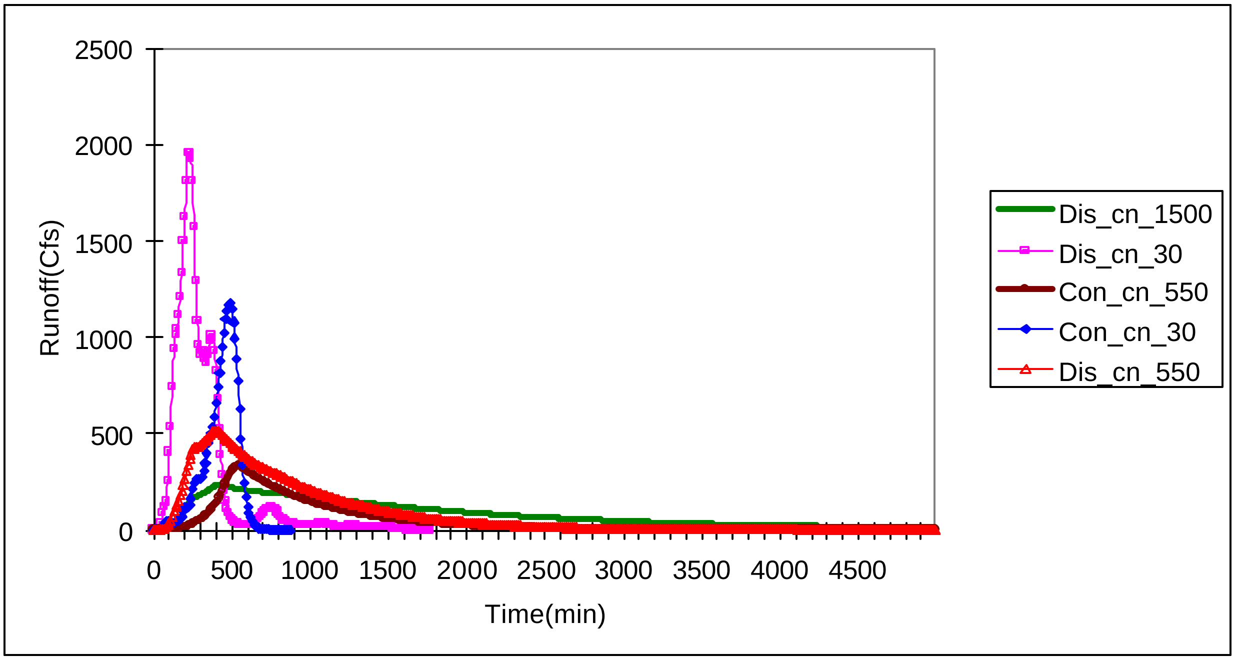

Figure 7-38 Effect of distribution of Curve Numbers and Storage factor on the 10 minute DRHs for Thompson Run with Distributed Precipitation

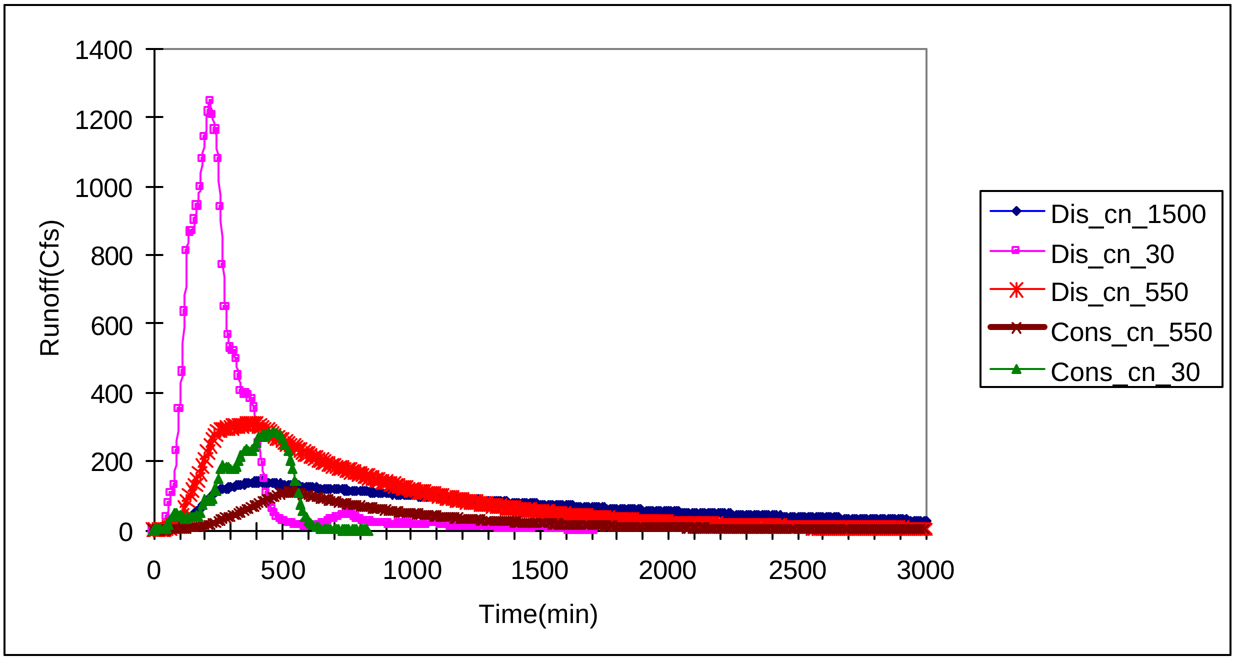

Figure 7-39 Effect of distribution of Curve Numbers and Storage factor on the 10 minute DRHs for Thompson Run with Unit Precipitation

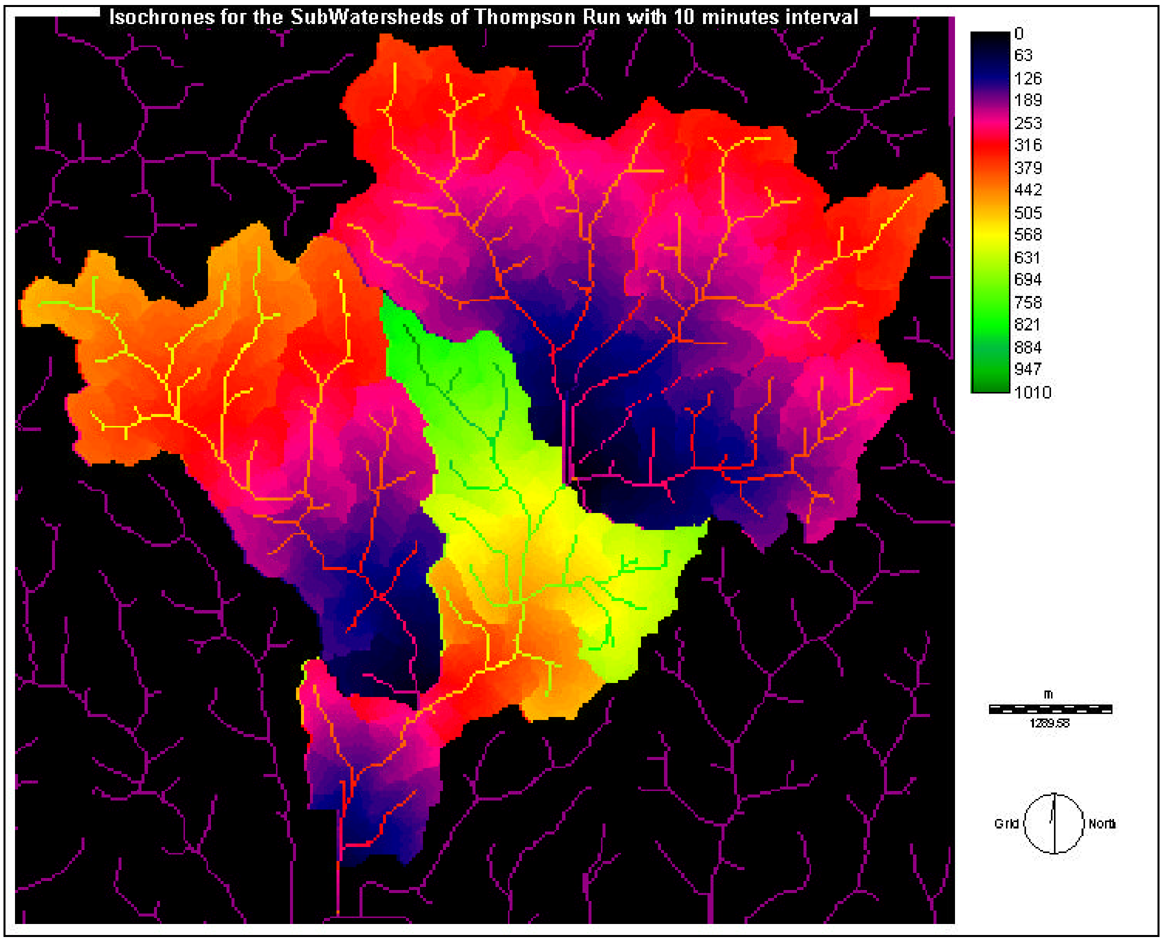

Figure 7-40 Isochrones with 10 minute time interval for the individual sub watersheds of Thompson Run Watershed

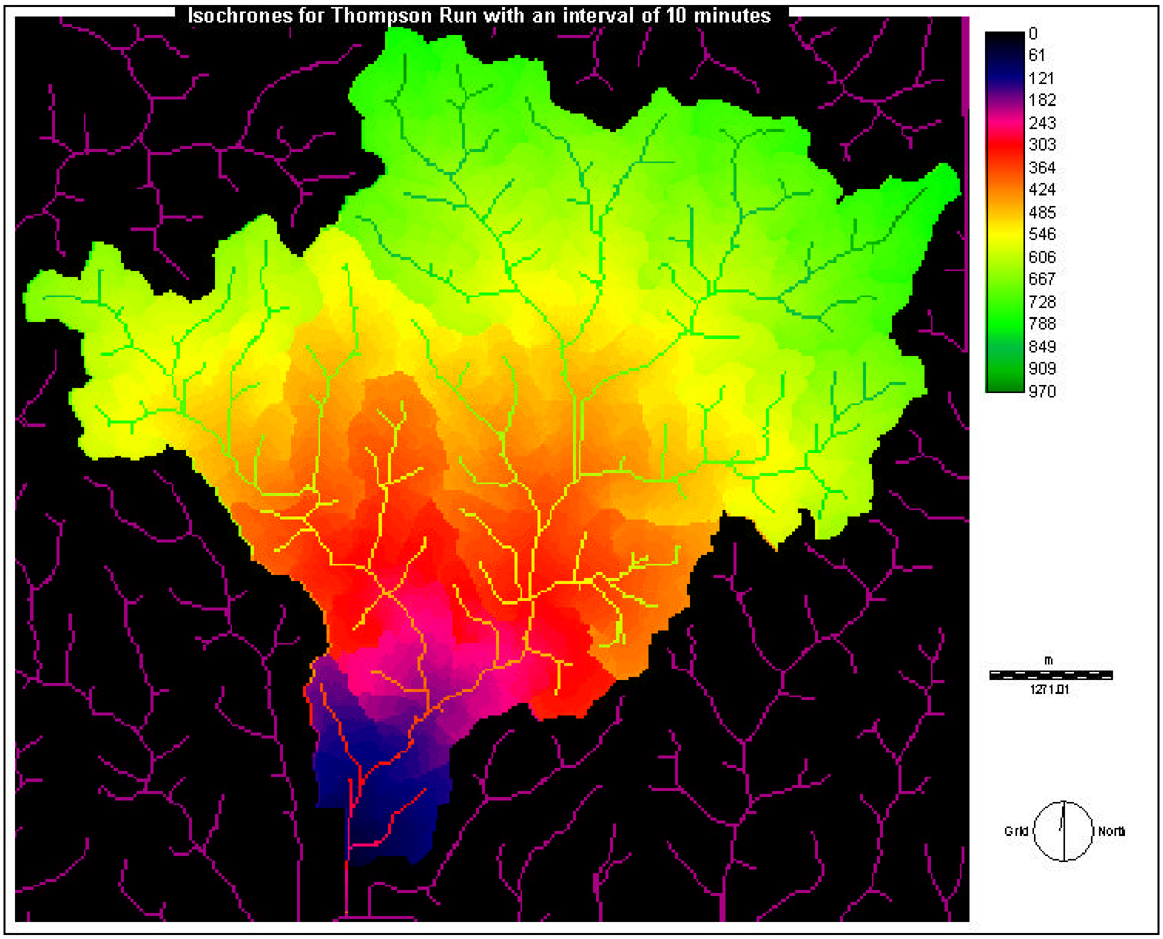

Figure 7-41 Isochrones with 10 minute time interval for the whole Thompson Run Watershed

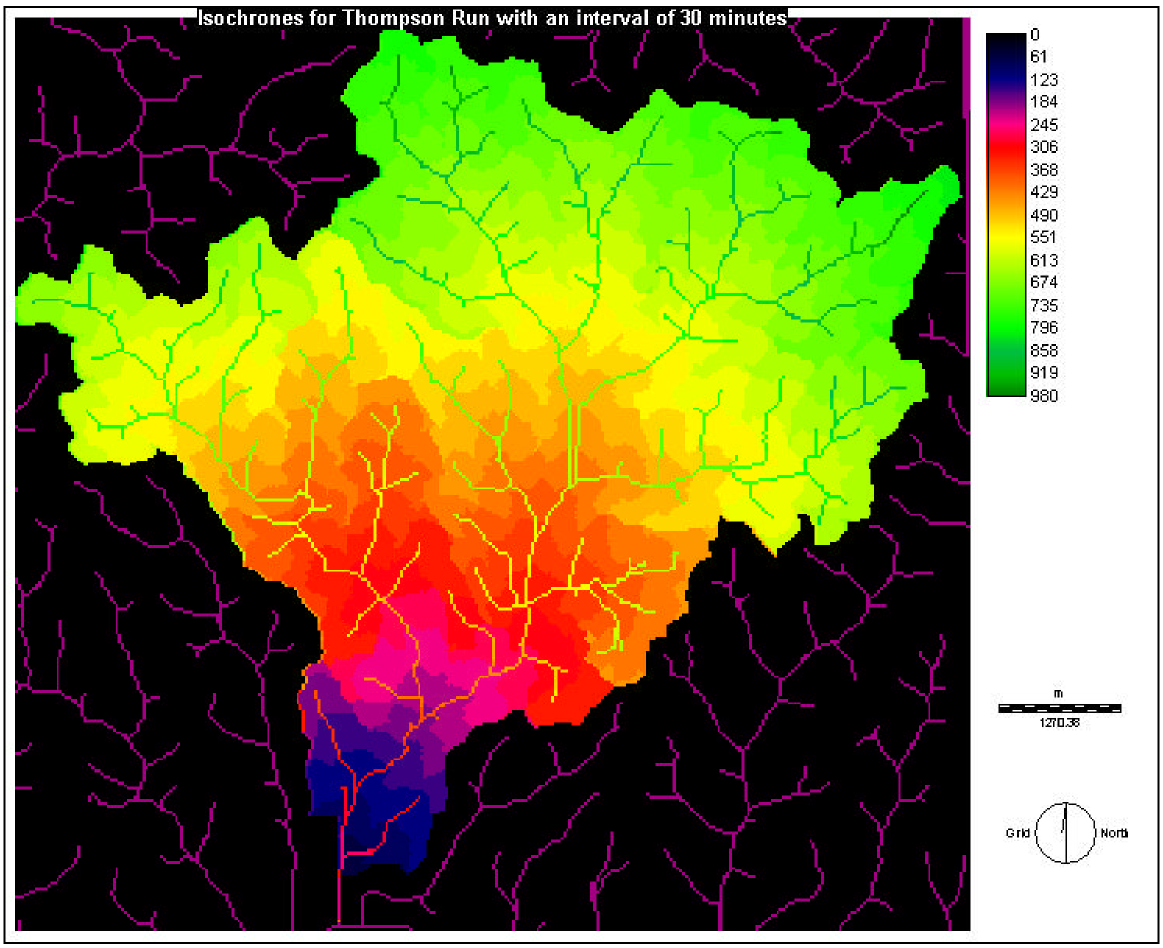

Figure 7-42 Isochrones with 30 minute time interval for the whole Thompson Run Watershed

7.3 Effect of Resolution

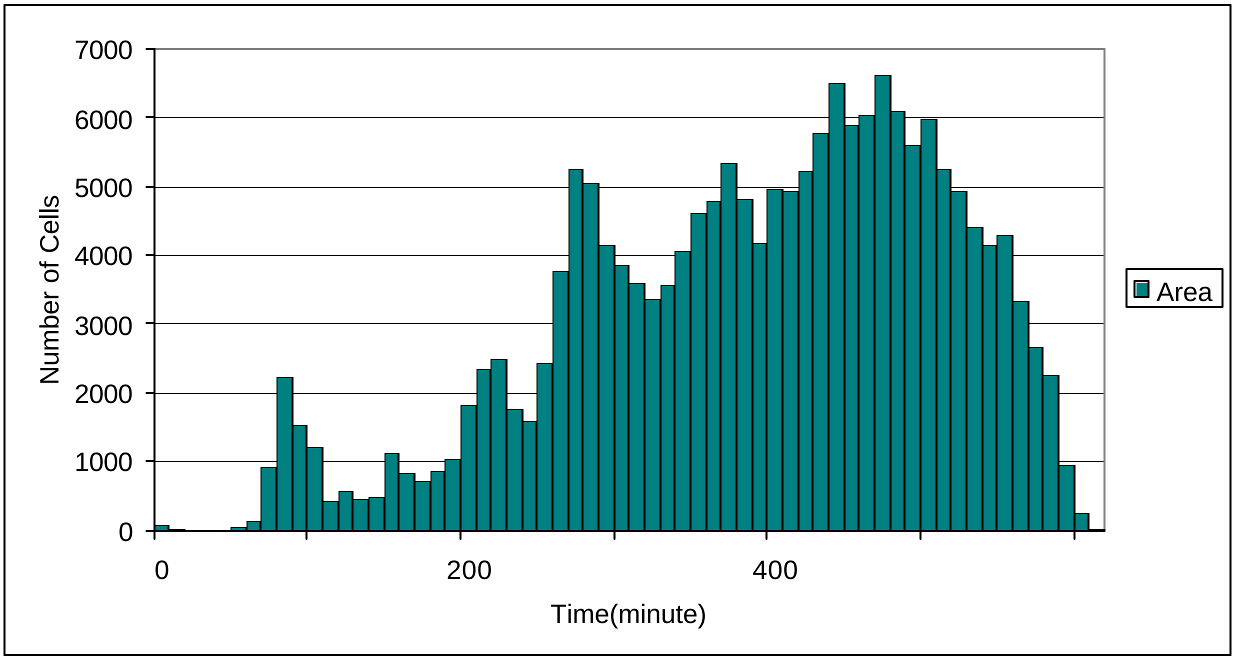

Figure 7-43 Time area histogram for Thompson Run with grid size of 15 meters

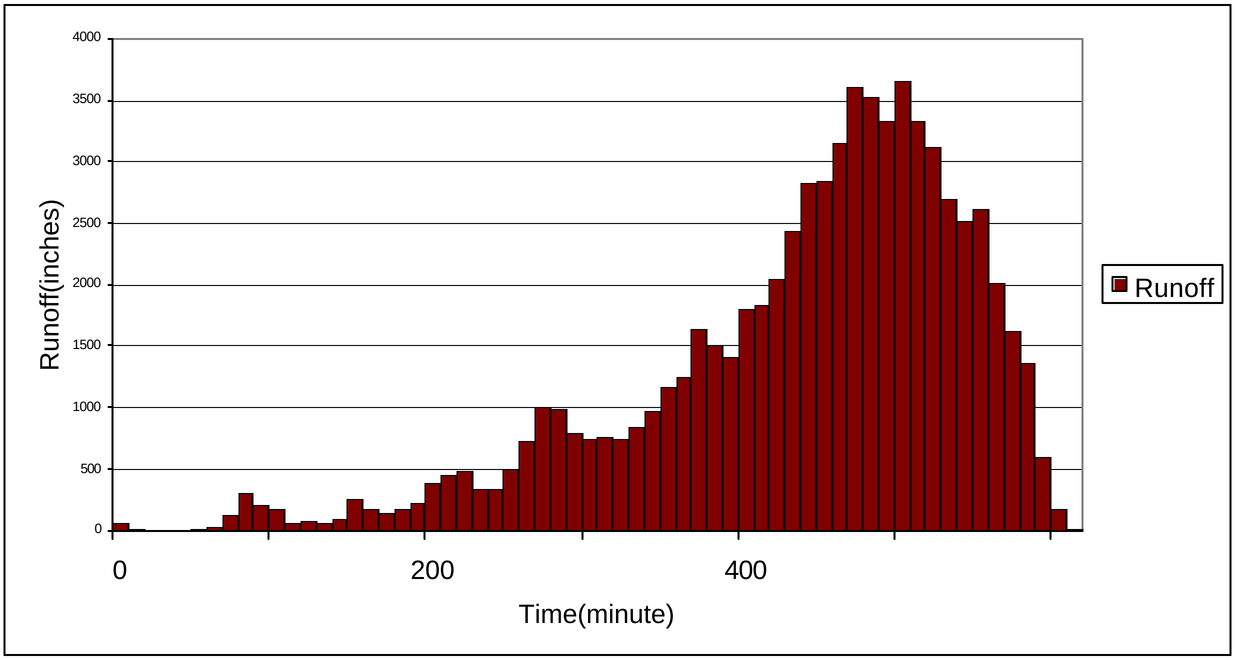

Figure 7-44 Runoff time histogram for Thompson Run with grid size of 15 meters

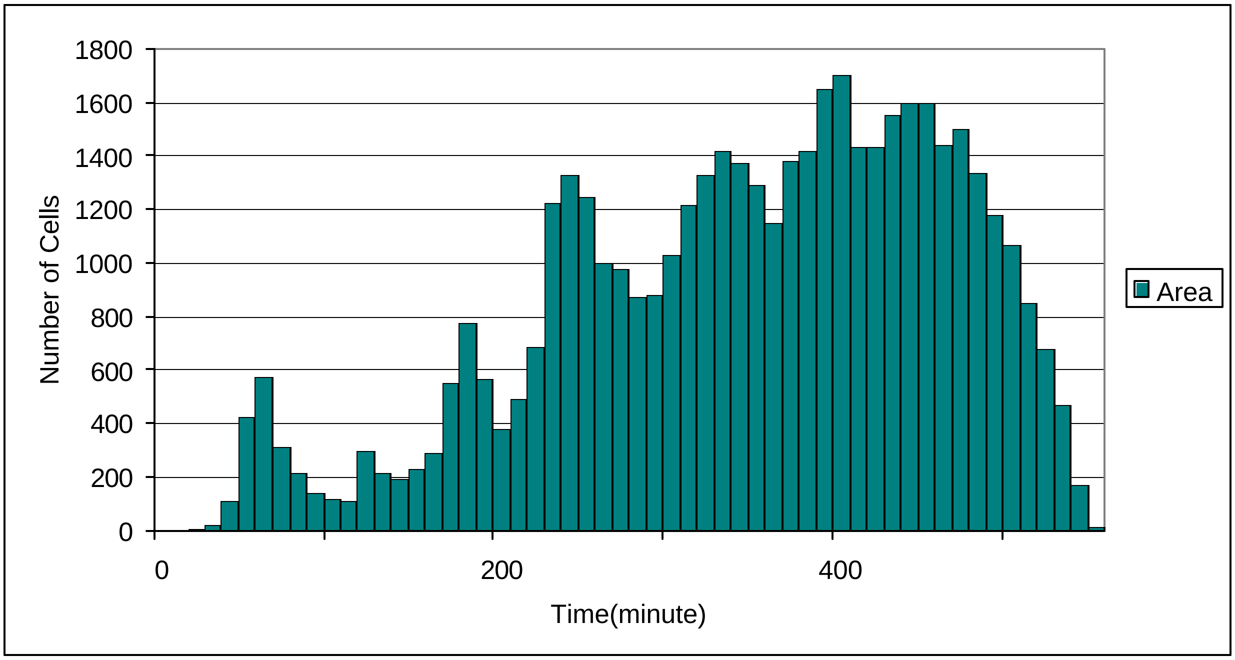

Figure 7-45 Time area histogram for Thompson Run with grid size of 30 meters

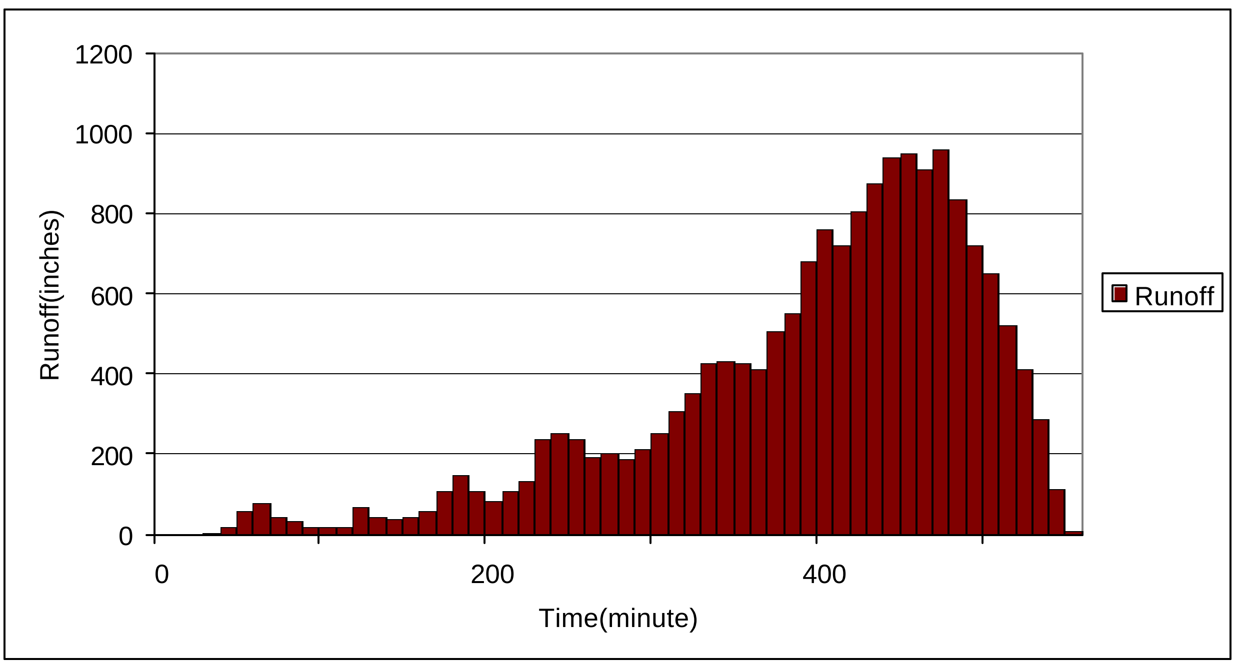

Figure 7-46 Runoff time histogram for Thompson Run with grid size of 30 meters

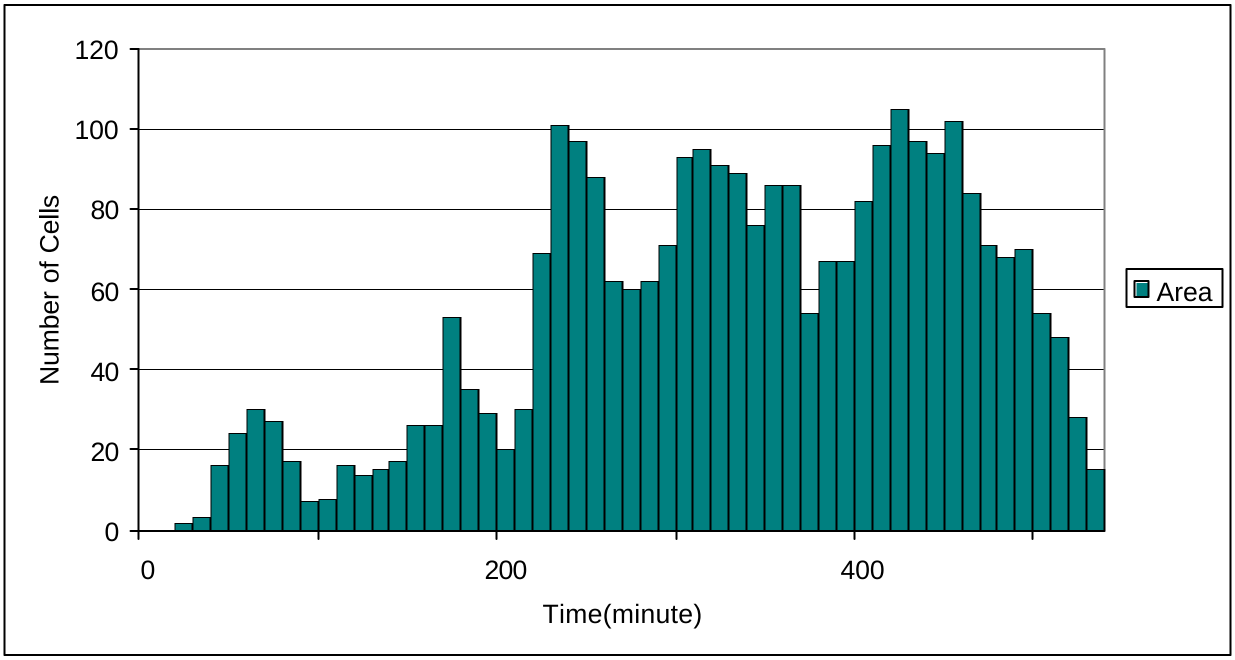

Figure 7-47 Time area histogram for Thompson Run with grid size of 120 meters

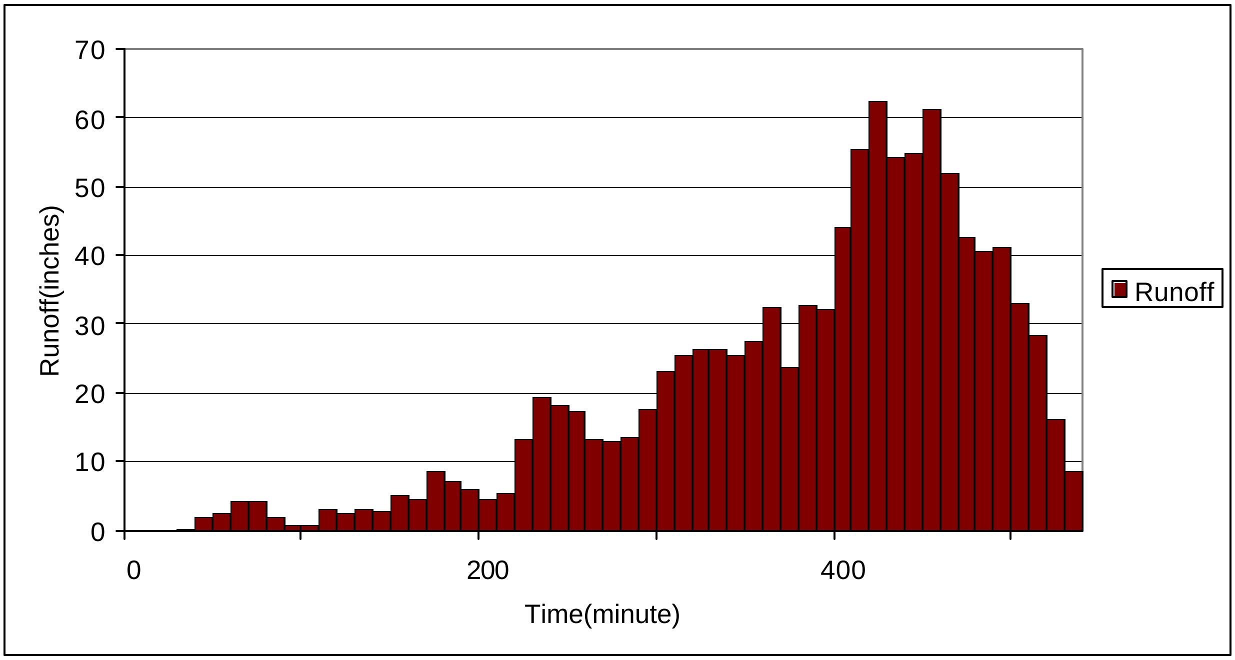

Figure 7-48 Runoff time histogram for Thompson Run with grid size of 120 meters

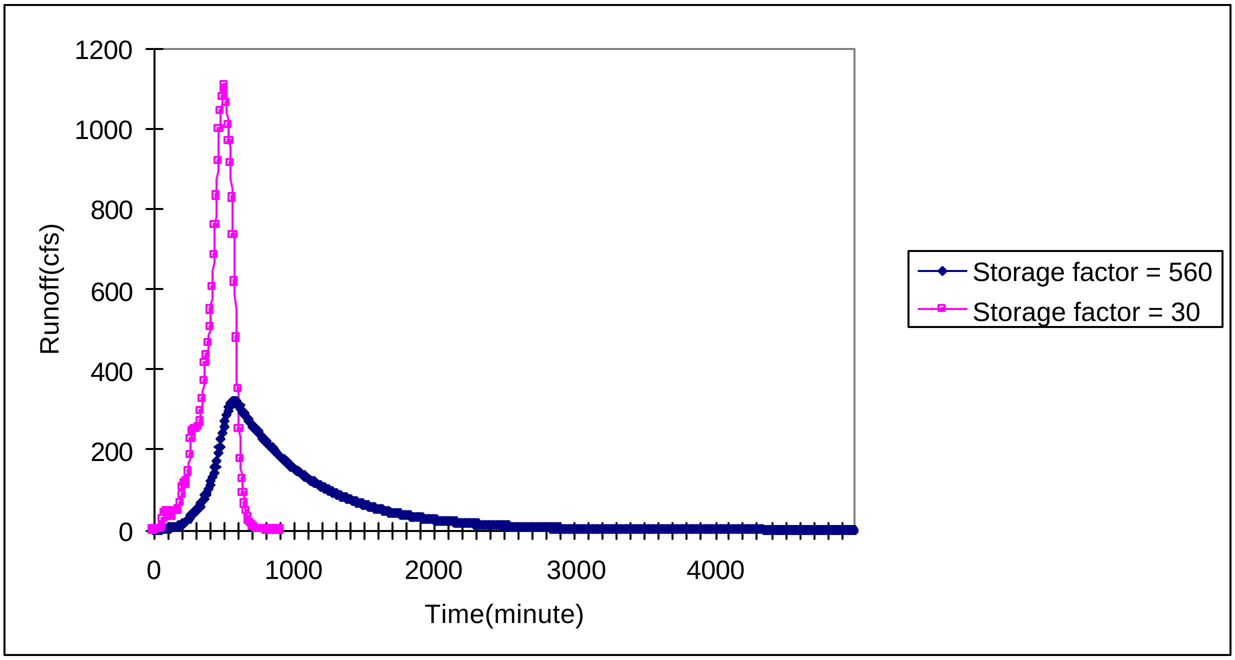

Figure 7-49 DRH for Thompson Run with grid size of 15 meters

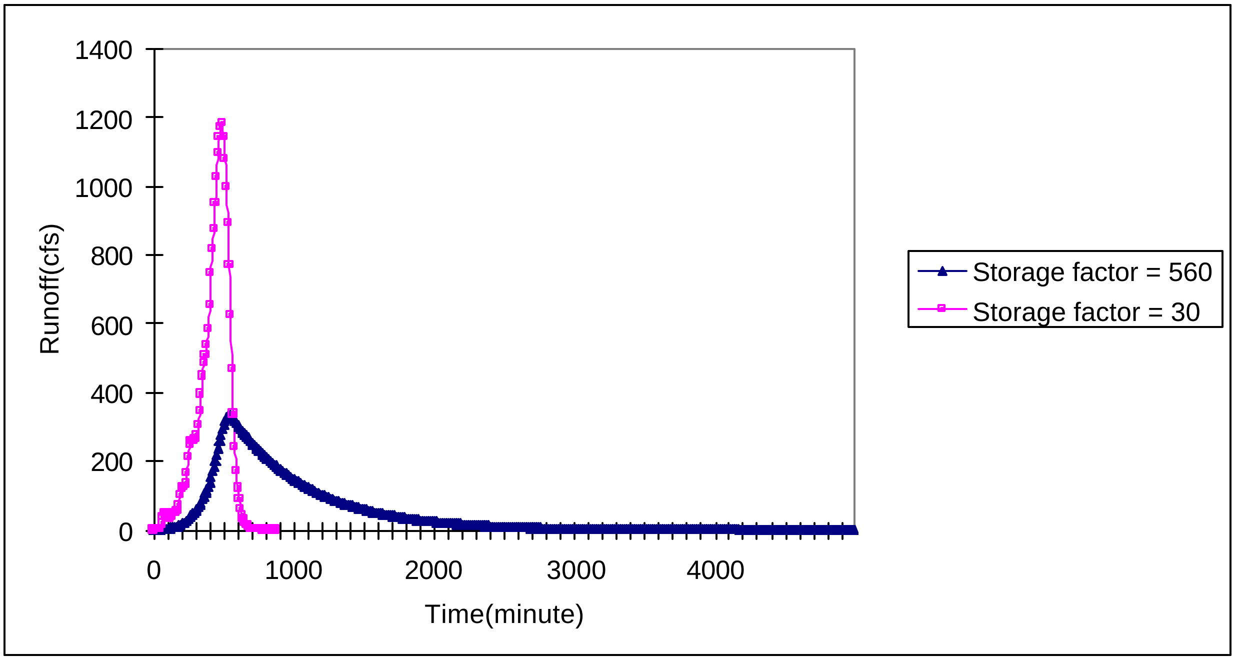

Figure 7-50 DRH for Thompson Run with grid size of 30 meters

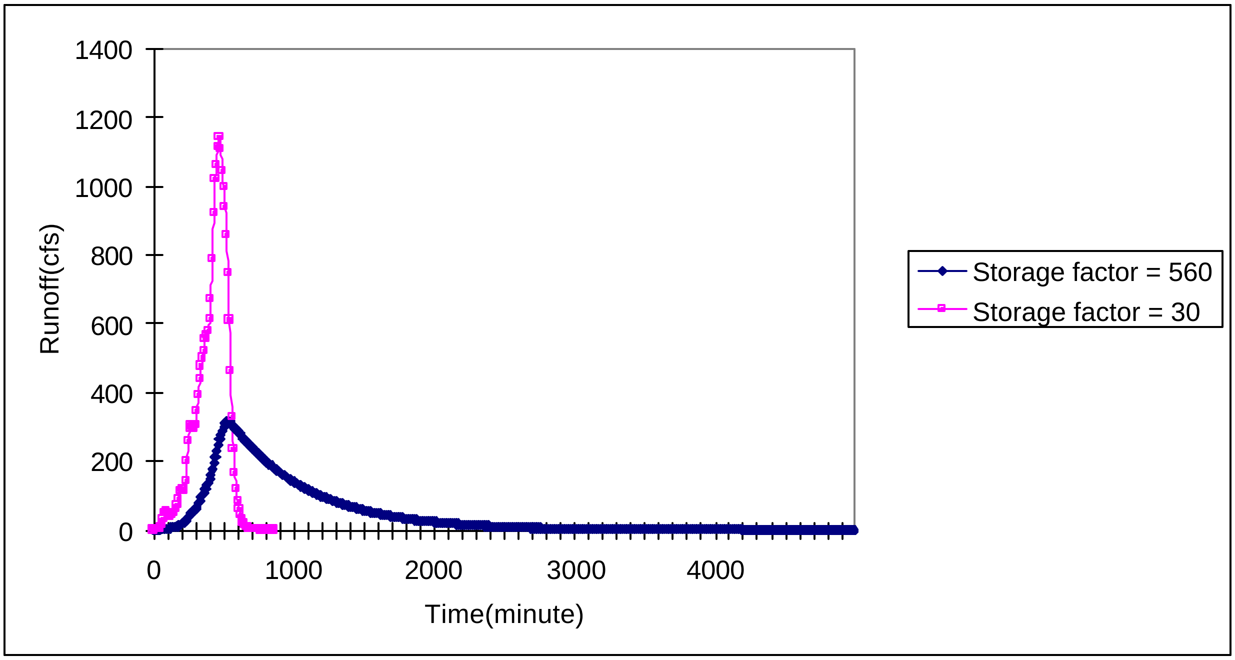

Figure 7-51 DRH for Thompson Run with grid size of 120 meters

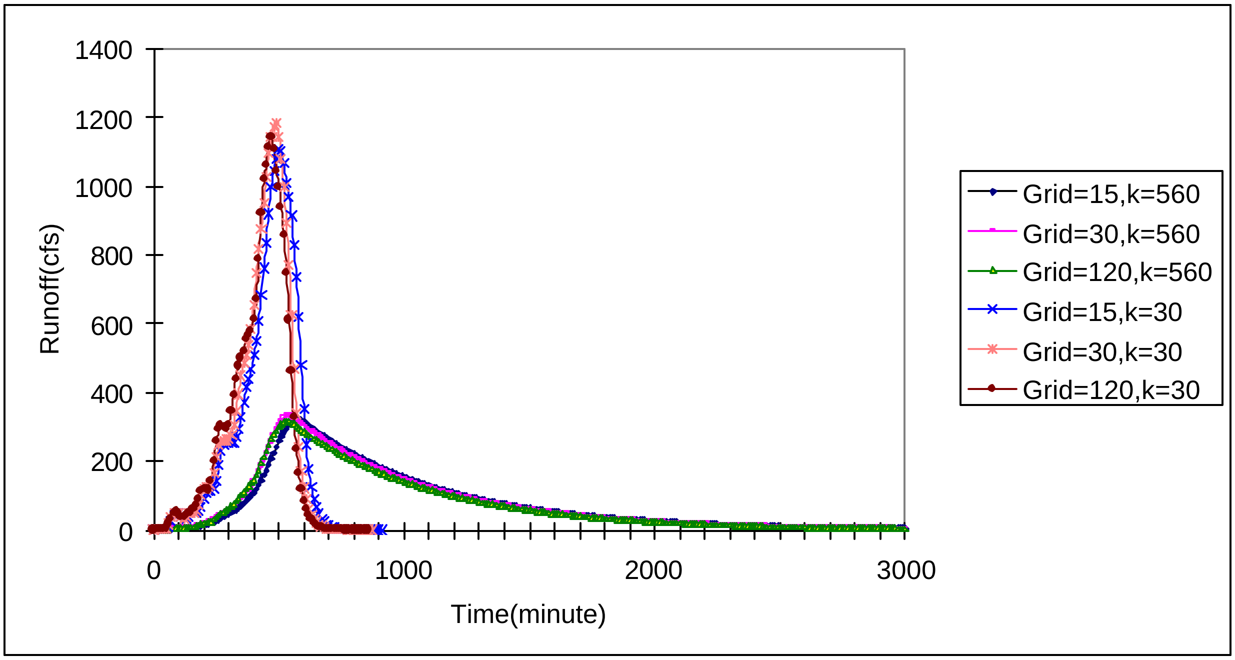

Figure 7-52 Effect of the grid size and storage factor on the DRHs of Thompson Run Watershed

CHAPTER 8

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 Discussion of Results

The objectives of this study were to generate the isochrones for the watersheds, to generate a spatially generated curve numbers data set for the watersheds and also to incorporate the spatial distribution of the curve numbers and the precipitation data into a model that would generate the runoff hydrographs for the watersheds.

The isochrones and the curve numbers data set were developed to satisfaction. The other results were obtained to demonstrate the effect of the spatial variation of the curve numbers and the precipitation. The results also presented the effect of the storage factor.

For the Thompson Run watershed, the unit precipitation time-area and time-runoff histograms for the two cases of distributed curve numbers and a single curve number show a marked difference. For unit precipitation, the time-area histogram can be taken to represent the input into the hydrologic model and the time-runoff histogram can be taken to represent the output from the system, with the retention effect of the curve numbers as the response function for the watershed. For the distributed curve numbers, the distribution of the runoff is more arbitrary, that is, it shows more variation and is spread over a larger time span, that is, the time of concentration is large. Whereas for the single curve number, the variation in the runoff is more gradual (with less spikes) and the time of concentration is smaller than that of the distributed curve numbers (about one third).

The effect of using a larger storage factor when routing the flow is that it makes the direct runoff hydrograph a single peak hydrograph. It also reduces the peak flow discharge and brings about a lot of attenuation thereby increasing the base time of the hydrograph.

The effect of the variation of the watershed parameter (curve number) and the precipitation is more profound in the case of lower storage factor, where one can observe larger runoff values, more peaks and reduced base time of the hydrograph.

For the Thompson Run watershed, for both cases of distributed precipitation and unit precipitation, the amount of runoff generated with distributed curve numbers exceeds the runoff volume generated with a single curve number. Therefore, the distributed curve numbers produce more runoff volume. The peak flow discharge for the distributed curve numbers is invariably larger than the single curve number (for small as well as large storage factors). The time to peak is less for the distributed curve numbers.

Thus for the cases studied the effect of the spatial distribution of curve numbers may be summarized as:

1) Distributed curve numbers generate higher runoff volume.
2) Distributed curve numbers generate higher peak flow discharge values.
3) The time to peak with the distributed curve numbers is less.

In all the distributed curve numbers produce more drastic results, giving design parameter values on the higher side. Thus the design of the hydraulic structures based on such an analysis would use a larger safety factor.

The study of the effect of resolution or the grid size of the Digital Elevation Model of the watershed for the Thompson Run watershed showed that there is very little variation in the peak flow of the hydrographs and also in the time to peak. This lack of significant variation in the hydrographs may be attributed to the formula that was employed in this study for the calculation of the lag time. The formula takes into consideration only the distance of the source cell from the outlet and hence the reduction of the cell size was counter balanced by the corresponding increase in the number of cells, thus giving no variation in the hydrographs for different grid sizes.

The results obtained in this study were successful in demonstrating the effect of the spatial distribution of the parameters and also the spatial distribution of the inputs to a hydrologic system.

8.2 Conclusions and Recommendation for further study

The routing technique used in this study is a lumped routing. To make the model truly distributed in nature the kinematic routing technique should be used, which would trace the runoff from each cell to the outlet. As mentioned in the section 2.3.3, St. Venant's equations need to be used if one wants to fully explain the dispersion process along with the storage effects of the watershed. But this could be too cumbersome. The curve numbers generated in this study assume the normal antecedent moisture conditions (AMC II). If the model is to be used for continuing storm analysis the dry conditions (AMC I) and wet conditions (AMC III) curves numbers would have to be calculated and used to update the basin response.

The precipitation data used in this study was not real but was generated in form of raster data file for simulation purposes. One of the objectives of this study was to demonstrate that the spatially distributed precipitation data can be incorporated into the present rainfall-runoff model. To design a truly distributed rainfall-runoff model, it is required that along with the watershed parameters (like curve numbers) the input into the hydrologic model (precipitation) is also spatially distributed.

The National Weather Service (NWS) in conjunction with the Departments of Defense and Transportation has deployed weather radars, the information from which, combined with the information from the rain gages and satellites, is used to generate high quality hourly precipitation estimates. The NWS produces gridded precipitation estimates as part of its Next Generation Weather Radar (NEXRAD) program. The NEXRAD data are hourly estimates in the Hydrologic Rainfall Analysis Project (HRAP) grid system, which is a 4km grid in Stereographic map projection. While the HRAP system is defined on a spherical datum most, of the GIS data sets describing the land surface, including the DEMs are typically defined on an ellipsoidal datum. Therefore, to incorporate this NEXRAD data into this model the HRAP grid system would have to be properly geo-referenced with the DEM.

Calibrated radar rainfall systems are becoming more popular due to advantages they offer over conventional precipitation monitoring systems. One such system is CALAMAR provided by 3RWWDP (3 Rivers Wet Weather Demonstration Program) to help assist communities with the sewage overflow problems in the Allegheny County of Pennsylvania. The process creates a "virtual rain gauge", measuring rainfall in a manner similar to that of a rain gauge for every square kilometer in the Allegheny County Sanitary Authority service area.

APPENDIX A

APPENDIX – A

FORTRAN CODES FOR SPECIALIZED PROGRAMS

MOD_TA&EX_V+SCS

```
C     *********************************************************************
C
C     *********************************************************************
C     PROGRAM MOD_TA&EX_V+SCS.FOR
C     USES SCS METHOD FOR CALCULATING THE TIME OF CONCENTRATION
C     FOR THE WATERSHED
C     IT CREATES THE FOLLOWING FILES
C      1) THE DATA FILE WITH THE TIME-AREA CO-ORDINATES
C     2) THE T-A.TXT FILE WITH THE TIME-AREA CO-ORDINATES TO BE USED FOR THE
C        UNIT HYDROGRAPH GENERATION
C        3) THE EX_PREC.TXT FILE WITH THE TIME-EXCESS PRECIPITATION CO-ORDINATES TO BE USED FOR THE
C        RUNOFF HYDROGRAPH GENERATION
C     4) THE ISOCHROMES FILES WHICH CONTAINS THE ISOCHROMES OF THE INPUT TIME
C        INTERVAL FOR THE INCUMBENT WATERSHED
C     5) THE RECORD.TXT FILE WHICH RECORDS ALL THE CALCULTATIONS AND VALUES
C     *********************************************************************
C
C     *********************************************************************
C      THIS PROGRAM WAS ORIGINALLY WRITTEN BY MARK MICHELINI AND HAS BEEN MODIFIED BY
C        KHALID KHAN TO INCORPORATE THE ISOCHROMES GENERATION AND INCLUSION OF THE GRIDDED
C          PRECIPITATION DATA.IT IS TO BE NOTED THAT THE PRECIPITATION DATA IS INCORPOATED
C     IN FORM OF A RASTER FILE.
C      THE ARRAYS HAVE ALSO BEEN MODIFIED TO EXECUTE LARGER FILES (UPTO 1500 COLUMNS)
C     *********************************************************************

      INTEGER*2 BUFFER(1500,3),DIR(1500,3),NEWBUF(1500,3),ELEVS(1500,3)
          INTEGER*2 ISOBUF(1500,3),CNBUF(1500,3)
C         INTEGER*2 PRECBUF(1500,3)
          REAL*4 PRECBUF(1500,3)
      CHARACTER*80 ELFILE,SFILE,DFILE,WFILE,PRECFILE,ISOFILE,CNFILE
      REAL SIZE,TC,MAXSUM,MXCSUM,MXSLOP,RET,SLOPE,SUM_PE,AVE_PE
          INTEGER*2 TT
      INTEGER Q,INTERV,TOT,CN,CNN,T
          INTEGER TA(9000)
          REAL EX_PE(9000)
      LOGICAL ACTIV
      LUNIT=7
```

```
      PUNIT=12
      DUNIT=14
          ISOUNIT=18
          PRECUNIT=17
          CNUNIT=19
      PRINT 10
10    FORMAT(/,'---- OUTPUT FILE IS NAMED "DATA" ----')
      PRINT 1
1     FORMAT(/,'*** ENTER LENGTH AND WIDTH OF FILE ***')
      READ (*,*)NL,NS
      PRINT 2
2     FORMAT('*** ENTER ELEVATION FILE ***')
      READ (5,1000)ELFILE
      PRINT 3
3     FORMAT('*** ENTER WATERSHED FILE ***')
      READ (5,1000)WFILE
      PRINT 4
4     FORMAT('*** ENTER STREAM FILE ***')
      READ (5,1000)SFILE
      PRINT 5
5     FORMAT('*** ENTER DIRECTION FILE ***')
      READ (5,1000)DFILE
      PRINT 13
13    FORMAT('*** ENTER ISOCHRONES FILE ***')
      READ (5,1000)ISOFILE
          PRINT 41
41    FORMAT('*** ENTER PRECIPITATION FILE ***')
      READ (5,1000)PRECFILE
          PRINT 42
42    FORMAT('*** ENTER CURVE NUMBER FILE ***')
      READ (5,1000)CNFILE
      PRINT 6
6     FORMAT('*** ENTER THE GRID SIZE---METERS ***')
      READ (5,*)SIZE
      PRINT 7
7     FORMAT('*** ENTER WATERSHED NUMBER ***')
      READ (5,*)Q
      PRINT 8
8     FORMAT('*** ENTER AVERAGE VALUE OF CN FOR THE WATERSHED ***')
      READ (5,*)CN
      PRINT 9
9     FORMAT('*** ENTER TIME INTERVAL IN MINUTES ***')
      READ (5,*)INTERV
1000  FORMAT(A80)
C
C     OPENING FILES UNDER UNIX OR DOS
C
      OPEN(UNIT=LUNIT,STATUS='OLD',RECL=NS*2,
     * FORM='UNFORMATTED',ACCESS='DIRECT',FILE=ELFILE)
      OPEN(12,STATUS='OLD',RECL=NS*2,
     * FORM='UNFORMATTED',ACCESS='DIRECT',FILE=WFILE)
      OPEN(16,STATUS='OLD',RECL=NS*2,
     * FORM='UNFORMATTED',ACCESS='DIRECT',FILE=SFILE)
      OPEN(14,STATUS='OLD',ACCESS='DIRECT',FILE=DFILE,
     * RECL=NS*2,FORM='UNFORMATTED')
          OPEN(17,STATUS='OLD',ACCESS='DIRECT',FILE=PRECFILE,
```

```
     * RECL=NS*4,FORM='UNFORMATTED')
C      OPEN(17,STATUS='OLD',ACCESS='DIRECT',FILE=PRECFILE,
C     * RECL=NS*2,FORM='UNFORMATTED')
          OPEN(18,STATUS='UNKNOWN',ACCESS='DIRECT',FILE=ISOFILE,
     * RECL=NS*2,FORM='UNFORMATTED')
      OPEN(19,STATUS='UNKNOWN',ACCESS='DIRECT',FILE=CNFILE,
     * RECL=NS*2,FORM='UNFORMATTED')
C
C          STARTING THE PROCESSING
C     INITIALIZING THE CONSTANTS
C
      DIST=SIZE
      XDIST=SQRT(2*SIZE*SIZE)
      KOUNT=0
      KOUNT1=0
          SUM_PE=0.0
          OPEN(3,FILE='RECORD.TXT',STATUS='UNKNOWN')
C      RET=(1000/CN)-10
C
C     INITIALIZING THE ISOCHROMES FILE
C
          DO 711 I=1,NL
          DO 712 J=1,NS
          ISOBUF(J,1)=0
          WRITE (18,REC=I) (ISOBUF(J,1),J=1,NS)
712       CONTINUE
711       CONTINUE
C
C     FINDING THE BOTTOM ELEVATION
C
      DO 15 I=1,NL
      READ (16,REC=I) (BUFFER(J,1),J=1,NS)
      READ (LUNIT,REC=I) (ELEVS(J,1),J=1,NS)
      DO 14 J=1,NS
      IF(BUFFER(J,1).EQ.2) THEN
        BOTELV=ELEVS(J,1)
        GO TO 17
        ENDIF
14    CONTINUE
15    CONTINUE
C
C    INITIALIZE TIMES --INTERV = INTERVAL,(TOTAL OF 250)
C
17    MAXINT=INTERV*250
      DO 22 T=INTERV,MAXINT,INTERV
22    TA(T)=0
      EX_PE(T)=0.0
C
C     TMAX1 IS ACTUAL TIME OF CONCENTRATION
C
      TMAX=0
      TMAX1=0.
      MAXSUM=0.
      MXCSUM=0.
      N=2
C
```

```
C    READING THE FILES
C
60   KOUNT=KOUNT+1
     KOUNT1=KOUNT1+1
     SUM=0.
     CSUM=0.
     I1=1
     I2=2
     I3=3
     READ (12,REC=N-1) (NEWBUF(K,1),K=1,NS)
     READ (12,REC=N) (NEWBUF(K,2),K=1,NS)
     READ (12,REC=N+1) (NEWBUF(K,3),K=1,NS)
     READ (16,REC=N-1) (BUFFER(K,1),K=1,NS)
     READ (16,REC=N) (BUFFER(K,2),K=1,NS)
     READ (16,REC=N+1) (BUFFER(K,3),K=1,NS)
     M=N
     ACTIV=.TRUE.
C
C    IDENTIFYING THE CELLS THAT FALL IN THE INCUMBENT WATERSHED
C
     DO 30 I=N,NL-1
     DO 25 K=2,NS-1
     IF(NEWBUF(K,I2).NE.Q)GOTO 25
     IF(BUFFER(K,I2).LE.0)THEN
          NEWBUF(K,I2)=TT
          GO TO 23
          ENDIF
     IF (BUFFER(K,I2).EQ.1)THEN
          NEWBUF(K,I2)=TT
          ACTIV=.FALSE.
          GO TO 23
          ENDIF
     IF (BUFFER(K,I2).EQ.2)THEN
          NEWBUF(K,I2)=TT
          WRITE (12,REC=M) (NEWBUF(L,I2),L=1,NS)
                GO TO 60
          ENDIF
23   READ (LUNIT,REC=M)(ELEVS(J,1),J=1,NS)
     MIDELV=ELEVS(K,1)
     TOPELV=ELEVS(K,1)
     J=K
     GO TO 35
25   CONTINUE
     ITEMP=I1
     I1=I2
     I2=I3
     I3=ITEMP
     N=N+1
     M=M+1
     IF(I.EQ.NL-1)GO TO 200
     READ (12,REC=M+1) (NEWBUF(K,I3),K=1,NS)
     READ (16,REC=M+1) (BUFFER(K,I3),K=1,NS)
30   CONTINUE
35        WRITE (12,REC=M) (NEWBUF(K,I2),K=1,NS)
     WRITE (18,REC=M) (NEWBUF(K,I2),K=1,NS)
     SUM=0.
```

```
      READ (16,REC=M) (BUFFER(K,I2),K=1,NS)
      READ (14,REC=M) (DIR(K,I2),K=1,NS)
            READ (17,REC=M) (PRECBUF(K,I2),K=1,NS)
            READ (19,REC=M) (CNBUF(K,I2),K=1,NS)

C
C     GIVING THE WEIGHTED VALUE TO THE AREA ORDINATE FOR THE TIME AREA PLOT
C     THE WEIGHTS ARE THE PRECIPITATION THE CELL RECIEVES WHICH IS PICKED
C     FROM THE PRECIPITATION RASTER FILE(PRECFILE)
C
C           TA(T)=TA(T)+1*PRECBUF(J,I2)
C           PRINT *,M,TA(T),PRECBUF(J,I2)
      P=PRECBUF(J,I2)
            CNN=CNBUF(J,I2)
            RET=(1000/CNN)-10
            CALL EXCESS(PE,P,RET)
            TA(T)=TA(T)+1
            EX_PE(T)=EX_PE(T)+PE
            SUM_PE=SUM_PE+PE
c           PRINT *,M,CNN,TA(T),P,PE,EX_PE(T)
            WRITE(3,*) M,CNN,T,TA(T),P,PE,EX_PE(T)

66    IF(ACTIV)GO TO 75
      GO TO 185
75    IF(BUFFER(J-1,I2).LE.0.AND.DIR(J,I2).EQ.32)THEN
          SUM=SUM+DIST
          J=J-1
          GO TO 66
          ENDIF
      IF(BUFFER(J,I1).LE.0.AND.DIR(J,I2).EQ.128)THEN
          SUM=SUM+DIST
          GO TO 160
          ENDIF
      IF(BUFFER(J+1,I2).LE.0.AND.DIR(J,I2).EQ.2)THEN
          SUM=SUM+DIST
          J=J+1
          GO TO 66
          ENDIF
      IF(BUFFER(J,I3).LE.0.AND.DIR(J,I2).EQ.8)THEN
          SUM=SUM+DIST
          GO TO 140
          ENDIF
      IF(BUFFER(J-1,I1).LE.0.AND.DIR(J,I2).EQ.64)THEN
          SUM=SUM+XDIST
          J=J-1
          GO TO 160
          ENDIF
      IF(BUFFER(J+1,I1).LE.0.AND.DIR(J,I2).EQ.1)THEN
          SUM=SUM+XDIST
          J=J+1
          GO TO 160
          ENDIF
      IF(BUFFER(J+1,I3).LE.0.AND.DIR(J,I2).EQ.4)THEN
          SUM=SUM+XDIST
          J=J+1
          GO TO 140
```

```
      ENDIF
   IF(BUFFER(J-1,I3).LE.0.AND.DIR(J,I2).EQ.16)THEN
      SUM=SUM+XDIST
      J=J-1
      GO TO 140
      ENDIF
   GO TO 180
140  ITEMP=I1
   I1=I2
   I2=I3
   I3=ITEMP
   M=M+1
   READ (14,REC=M) (DIR(K,I2),K=1,NS)
   READ (16,REC=M+1) (BUFFER(K,I3),K=1,NS)
   GO TO 66
160  M=M-1
   ITEMP=I3
   I3=I2
   I2=I1
   I1=ITEMP
   READ (14,REC=M)(DIR(K,I2),K=1,NS)
   READ (16,REC=M-1)(BUFFER(K,I1),K=1,NS)
   GO TO 66
180  CSUM=0.
   IF(BUFFER(J-1,I2).EQ.1.AND.DIR(J,I2).EQ.32)THEN
      SUM=SUM+DIST
      READ(LUNIT,REC=M)(ELEVS(K,1),K=1,NS)
      MIDELV=ELEVS(J-1,1)
      J=J-1
      ACTIV=.FALSE.
      GO TO 66
      ENDIF
   IF(BUFFER(J,I1).EQ.1.AND.DIR(J,I2).EQ.128)THEN
      SUM=SUM+DIST
      READ(LUNIT,REC=M-1)(ELEVS(K,1),K=1,NS)
      MIDELV=ELEVS(J,1)
      ACTIV=.FALSE.
      GO TO 160
      ENDIF
   IF(BUFFER(J+1,I2).EQ.1.AND.DIR(J,I2).EQ.2)THEN
      SUM=SUM+DIST
      READ(LUNIT,REC=M)(ELEVS(K,1),K=1,NS)
      MIDELV=ELEVS(J+1,1)
      J=J+1
      ACTIV=.FALSE.
      GO TO 66
      ENDIF
   IF(BUFFER(J,I3).EQ.1.AND.DIR(J,I2).EQ.8)THEN
      SUM=SUM+DIST
      READ(LUNIT,REC=M+1)(ELEVS(K,1),K=1,NS)
      MIDELV=ELEVS(J,1)
      ACTIV=.FALSE.
      GO TO 140
      ENDIF
   IF(BUFFER(J-1,I1).EQ.1.AND.DIR(J,I2).EQ.64)THEN
      SUM=SUM+XDIST
```

```
          READ(LUNIT,REC=M-1)(ELEVS(K,1),K=1,NS)
          MIDELV=ELEVS(J-1,1)
          J=J-1
          ACTIV=.FALSE.
          GO TO 160
          ENDIF
      IF(BUFFER(J+1,I1).EQ.1.AND.DIR(J,I2).EQ.1)THEN
          SUM=SUM+XDIST
          READ(LUNIT,REC=M-1)(ELEVS(K,1),K=1,NS)
          MIDELV=ELEVS(J+1,1)
          J=J+1
          ACTIV=.FALSE.
          GO TO 160
          ENDIF
      IF(BUFFER(J+1,I3).EQ.1.AND.DIR(J,I2).EQ.4)THEN
          SUM=SUM+XDIST
          READ(LUNIT,REC=M+1)(ELEVS(K,1),K=1,NS)
          MIDELV=ELEVS(J+1,1)
          J=J+1
          ACTIV=.FALSE.
          GO TO 140
          ENDIF
      IF(BUFFER(J-1,I3).EQ.1.AND.DIR(J,I2).EQ.16)THEN
          SUM=SUM+XDIST
          READ(LUNIT,REC=M+1)(ELEVS(K,1),K=1,NS)
          MIDELV=ELEVS(J-1,1)
          J=J-1
          ACTIV=.FALSE.
          GO TO 140
          ENDIF
185   IF(BUFFER(J-1,I2).EQ.1.AND.DIR(J,I2).EQ.32)THEN
          CSUM=CSUM+DIST
          J=J-1
          GO TO 66
          ENDIF
      IF(BUFFER(J,I1).EQ.1.AND.DIR(J,I2).EQ.128)THEN
          CSUM=CSUM+DIST
          GO TO 160
          ENDIF
      IF(BUFFER(J+1,I2).EQ.1.AND.DIR(J,I2).EQ.2)THEN
          CSUM=CSUM+DIST
          J=J+1
          GO TO 66
          ENDIF
      IF(BUFFER(J,I3).EQ.1.AND.DIR(J,I2).EQ.8)THEN
          CSUM=CSUM+DIST
          GO TO 140
          ENDIF
      IF(BUFFER(J-1,I1).EQ.1.AND.DIR(J,I2).EQ.64)THEN
          CSUM=CSUM+XDIST
          J=J-1
          GO TO 160
          ENDIF
      IF(BUFFER(J+1,I1).EQ.1.AND.DIR(J,I2).EQ.1)THEN
          CSUM=CSUM+XDIST
          J=J+1
```

```
         GO TO 160
         ENDIF
      IF(BUFFER(J+1,I3).EQ.1.AND.DIR(J,I2).EQ.4)THEN
         CSUM=CSUM+XDIST
         J=J+1
         GO TO 140
         ENDIF
      IF(BUFFER(J-1,I3).EQ.1.AND.DIR(J,I2).EQ.16)THEN
         CSUM=CSUM+XDIST
         J=J-1
         GO TO 140
         ENDIF
      GO TO 190
190   IF(BUFFER(J-1,I2).EQ.2.AND.DIR(J,I2).EQ.32)THEN
         CSUM=CSUM+DIST
         GO TO 195
         ENDIF
      IF(BUFFER(J,I1).EQ.2.AND.DIR(J,I2).EQ.128)THEN
         CSUM=CSUM+DIST
         GO TO 195
         ENDIF
      IF(BUFFER(J+1,I2).EQ.2.AND.DIR(J,I2).EQ.2)THEN
         CSUM=CSUM+DIST
         GO TO 195
         ENDIF
      IF(BUFFER(J,I3).EQ.2.AND.DIR(J,I2).EQ.8)THEN
         CSUM=CSUM+DIST
         GO TO 195
         ENDIF
      IF(BUFFER(J-1,I1).EQ.2.AND.DIR(J,I2).EQ.64)THEN
         CSUM=CSUM+XDIST
         GO TO 195
         ENDIF
      IF(BUFFER(J+1,I1).EQ.2.AND.DIR(J,I2).EQ.1)THEN
         CSUM=CSUM+XDIST
         GO TO 195
         ENDIF
      IF(BUFFER(J+1,I3).EQ.2.AND.DIR(J,I2).EQ.4)THEN
         CSUM=CSUM+XDIST
         GO TO 195
         ENDIF
      IF(BUFFER(J-1,I3).EQ.2.AND.DIR(J,I2).EQ.16)THEN
         CSUM=CSUM+XDIST
         GO TO 195
         ENDIF
195   CDROP=MIDELV-BOTELV
      IF(CSUM.EQ.0)GO TO 198
      CSLOPE=CDROP/CSUM
      IF(CSLOPE.LT.0.001)CSLOPE=0.001
          TDROP=TOPELV-BOTELV
      TSUM=SUM+CSUM
      TSLOPE=TDROP/TSUM
          IF(TSLOPE.LT.0.001)TSLOPE=0.001
      IF(TSUM.GT.MAXSUM)THEN
         MAXSUM=TSUM
         SLOPE=TSLOPE
```

```
          ENDIF
      IF(CSUM.GT.MXCSUM)THEN
          MXCSUM=CSUM
          MXSLOP=CSLOPE
          ENDIF
C
C     GETTING THE VALUE OF THE VELOCITY FOR THE CELL
C
            CALL VELO(VEL,TSLOPE,CN)
            T_C=TSUM/VEL
            T_C=T_C/(INTERV*60)
            TT=INT(T_C)
            TT=(TT+1)*INTERV
C
C    CALCULATE TIME
C
C    TC IS TIME OF CONCENTRATION USING SCS METHOD
C    TMAX IS TIME OF CONCENTRATION FOR WATERSHED
C
      CALL TIME(TC,TSUM,RET,TSLOPE)
      IF(TC.GT.TMAX1)TMAX1=TC
      TC=TC/INTERV
      T=INT(TC)
      T=(T+1)*INTERV
      IF(T.GT.TMAX)TMAX=T
C
C     TA(INTERV) CORRESPONDS TO FIRST TIME INTERVAL
C     EXAMPLE-IF INTERVAL = 2 THEN TA(2) CORRESPONDS TO FIRST INTERVAL
C
      GO TO 170
170   IF(KOUNT.EQ.50)THEN
          PRINT*,'CELL',KOUNT1
          KOUNT=0
          ENDIF
198   GO TO 60
200   KOUNT1=KOUNT1-2
      CLOSE(12)
      CLOSE(14)
C
C     TOT IS THE NUMBER OF INTERVALS FOR USE IN PROGRAM HYDRO
C
      AVE_PE=SUM_PE/KOUNT1
      TOT=(INT(TMAX1/INTERV)+1)
            OPEN(5,FILE='EX_PREC.TXT',STATUS='UNKNOWN')
      OPEN(2,FILE='T-A.TXT',STATUS='UNKNOWN')
      OPEN(1,FILE='DATA.TXT',STATUS='UNKNOWN')
      WRITE(1,201)Q
      PRINT 201,Q
201   FORMAT(//,'WATERSHED NUMBER',I3)
      PRINT 202,KOUNT1
      WRITE (1,202) KOUNT1
202   FORMAT(//,'NUMBER OF CELLS =',I7)
      PRINT 203,CN
            WRITE (1,203) CN
203   FORMAT(//,'CURVE NUMBER =',I3)
      PRINT 204,AVE_PE
```

```
      WRITE (1,214) AVE_PE
214   FORMAT(//,'AVERAGE EXCESS RAINFALL FOR WATERSHED = ',F5.2)
      PRINT 204,MAXSUM,SLOPE
      WRITE(1,204)MAXSUM,SLOPE
204   FORMAT(//,'LONGEST FLOWPATH =',F9.2,' METERS',4X,'SLOPE = ',F7.4)
      PRINT 205,MXCSUM,MXSLOP
      WRITE(1,205)MXCSUM,MXSLOP
205   FORMAT('LENGTH OF MAINSTREAM =',F9.2,' METERS',4X,'SLOPE =',F7.4)
      PRINT 206,TMAX1
      WRITE (1,206) TMAX1
206   FORMAT('TIME OF CONCENTRATION =',F9.2,' MINUTES')
      PRINT 208,INTERV
      WRITE (1,208)INTERV
208   FORMAT('TIME INTERVAL =',I3,' MINUTES',/)
      PRINT 210,INTERV
      WRITE(1,210)INTERV
210   FORMAT('NO. OF CELLS PER TIME INTERVAL, STARTING AT',I3,' MIN')
      PRINT *,(TA(T), T=INTERV,TMAX,INTERV)
      WRITE (1,*) (TA(T), T=INTERV,TMAX,INTERV)
      WRITE(2,213)TOT
      WRITE(2,213)INTERV
      WRITE(5,213)TOT
      WRITE(5,213)INTERV
      DO 211 T=INTERV,TMAX,INTERV
      WRITE(2,213)(TA(T))
      WRITE(5,212)(EX_PE(T))
211   CONTINUE
C211  WRITE(2,213)(TA(T))
212   FORMAT(F15.5)
213   FORMAT(I5)
      STOP
      END
C
C
C     CALCULATING TIME OF CONCENTRATION BY SCS METHOD
C
C
      SUBROUTINE TIME(TC,D,R,S)
      REAL D,S,L,TC
      L=60*(D*3.281)**0.8*(R+1)**0.7/(1900*(S*100)**0.5)
      TC=L/0.6
      RETURN
      END
C
C
C     CALCUTATING THE VELOCITY FOR THE CELL
C     BASED ON THE SLOPE OF THE CELL USING THE
C     USING A FORMULA DEVELOPED FROM THE USDA 1986
C     GRAPH WHICH RELATES THE SLOPE AND THE
C     VELOCITY OF SHEET FLOW IN METERS PER SEC
C
C
      SUBROUTINE VELO(V,I,CNN)
      REAL I,V
      INTEGER CNN
      IF((CNN.GE.0).AND.(CNN.LE.50)) THEN
```

```
          V=0.041*EXP(0.2951*I)
          ELSEIF((CNN.GE.51).AND.(CNN.LE.60)) THEN
          V=0.0813*EXP(0.2836*I)
      ELSEIF((CNN.GE.61).AND.(CNN.LE.70)) THEN
          V=0.1217*EXP(0.2861*I)
          ELSEIF((CNN.GE.71).AND.(CNN.LE.75)) THEN
          V=0.1686*EXP(0.2882*I)
          ELSEIF((CNN.GE.76).AND.(CNN.LE.85)) THEN
          V=0.2533*EXP(0.2925*I)
          ELSEIF((CNN.GE.86).AND.(CNN.LE.100)) THEN
          V=0.3378*EXP(0.2885*I)
          ENDIF
          RETURN
          END
C
C    CALCULATING THE RAINFALL EXCESS
C
      SUBROUTINE EXCESS(A,C,B)
          REAL A,B,C
          IF(C.LT.0.2*B)THEN
          A=0.0
          ELSEIF (C.GE.0.2*B)THEN
          A=(C-0.2*B)**2/(C+0.8*B)
          ENDIF
          RETURN
          END
```

CURVE_NUMBER_KNK

```
C     *******************************************************************
C           PROGRAM CURVE_NUMBER_KNK FOR THE CALCULATION OF THE      CURVE NUMBER OF
            THE WATERSHED UNDER STUDY
C           AUTHOR: KHALID KHAN
C           DATE: 07/08/2001
C     *******************************************************************
C
C
C    INTITIALIZING THE DIFFERENT ARRAYS
C    WSBUF STORES THE READ IN DATA FROM THE WATERSHED FILE
C    SOILBUF STORES THE READ IN DATA FROM THE SOIL RASTER FILE
C    LANDBUF STORES THE READ IN DATA FROM THE LAND USE RASTER FILE
C    CNBUF STORES THE WRITTEN CURVE NUMBERS IN THE RASTER FILE
C
C
     INTEGER*2 WSBUF(1500,1500),SOILBUF(1500,1500),LANDBUF(1500,1500)
            INTEGER*2 CNBUF(1500,1500)
            INTEGER*2 CN(10000)
            INTEGER CURVE,N,SOIL,LAND,Q,NUM_CELLS,CURVE_NUMBER
     CHARACTER*80 WSFILE,SOILFILE,LANDFILE,CNFILE
C
C    GETTING THE INFORMATION ABOUT THE FILES FROM THE USER
C
     PRINT 1
1     FORMAT(/,'*** ENTER LENGTH AND WIDTH OF FILE***')
     READ(*,*)NL,NS
     PRINT 2
2     FORMAT('*** ENTER WATERSHED FILE***')
     READ(5,1000)WSFILE
            PRINT 3
3           FORMAT('*** ENTER THE WATERSHED NUMBER ***')
     READ(*,*)Q
            PRINT 4
4     FORMAT('*** ENTER THE SOIL RASTER FILE ***')
     READ(5,1000)SOILFILE
            PRINT 5
5           FORMAT('*** ENTER THE LAND USE RASTER FILE ***')
     READ(5,1000)LANDFILE
            PRINT 6
6     FORMAT('*** ENTER THE CURVE NUMBER FILE ***')
     READ(5,1000)CNFILE
1000  FORMAT (A80)
     WSUNIT=11
            SOILUNIT=12
            LANDUNIT=13
            CNUNIT=14
C
```

```
C     OPENING ALL THE FILES OLD AND NEW
C
      OPEN(11,FILE=WSFILE,STATUS='OLD',FORM='UNFORMATTED',
     * ACCESS='DIRECT',RECL=NS*2)
          OPEN(12,FILE=SOILFILE,STATUS='OLD',FORM='UNFORMATTED',
     * ACCESS='DIRECT',RECL=NS*2)
      OPEN(13,FILE=LANDFILE,STATUS='OLD',FORM='UNFORMATTED',
     * ACCESS='DIRECT',RECL=NS*2)
      OPEN(14,FILE=CNFILE,STATUS='UNKNOWN',FORM='UNFORMATTED',
     * ACCESS='DIRECT',RECL=NS*2)
C
C     INITIALIZING THE DIFFERENT COUNTERS AND THE NEW RASTER CN FILE TO 0s
C
      SUM=0
          NUM_CELLS=0
          DO 11 I=1,NL
          DO 12 J=1,NS
          CNBUF(J,1)=0
          WRITE (14,REC=I) (CNBUF(J,1),J=1,NS)
12        CONTINUE
11        CONTINUE
          N=2
          DO 30 I=N,NL-1
          READ(11,REC=I) (WSBUF(K,1),K=1,NS)
          READ(12,REC=I) (SOILBUF(K,1),K=1,NS)
          READ(13,REC=I) (LANDBUF(K,1),K=1,NS)
          DO 25 K=2,NS-1
C
C     PROCESSING ONLY THE CELLS THAT BELONG TO THE WATERSHED
C
          IF(WSBUF(K,1).NE.Q)GOTO 25
          NUM_CELLS=NUM_CELLS+1
          SOIL=SOILBUF(K,1)
          LAND=LANDBUF(K,1)
C
C     CALLING THE SUBROUTINE CURVE_NUM TO GET THE CURVE NUMBER FOR THE CELL
C
          CALL CURVE_NUM(CURVE,SOIL,LAND)
          WSBUF(K,1)=CURVE
          CN(CURVE)=CN(CURVE)+1
C
C     CREATING THE CURVE NUMBER RASTER FILE
C
          WRITE (14,REC=I) (WSBUF(J,1),J=1,NS)
25    CONTINUE
30    CONTINUE
      CLOSE(11)
          CLOSE(12)
          CLOSE(13)
C
C     CREATING THE CURVE NUMBER TEXT FILE WHICH GIVES THE DISTRIBUTION
C          OF THE CURVE NUMBERS AND CALCULATES THE AVERAGE CURVE NUBER FOR THE
WATERSHED
C
      OPEN(1,FILE='CNKNK.TXT',STATUS='UNKNOWN')
          PRINT 100
```

```
          WRITE(1,100)
100   FORMAT(//,30X,'THE CURVE-NUMBER CALCULATION FILE')
      PRINT 101
          WRITE(1,101)
101   FORMAT(30X,'---------------------------------')
          PRINT 102,Q
          WRITE(1,102)Q
102   FORMAT(///,10X,'WATERSHED NUMBER:',I3)
      PRINT 103,NUM_CELLS
          WRITE(1,103)NUM_CELLS
103   FORMAT(///,10X,'NUMBER OF CELLS IN THE WATERSHED:',I10)
          PRINT 104
          WRITE(1,104)
104   FORMAT(/////,10X,'CURVE NUMBER',20X,'NUMBER OF CELLS')
      PRINT 105
          WRITE(1,105)
105   FORMAT(10X,'-------------',20X,'----------------')
      DO 31 I=25,100
          SUM=SUM+I*CN(I)
          IF(CN(I).EQ.0)GOTO 31
          PRINT 106,I,CN(I)
          WRITE(1,106)I,CN(I)
31    CONTINUE
106   FORMAT(14X,I3,24X,I10)
      CURVE_NUMBER=INT(SUM/NUM_CELLS)+1
          PRINT 107,CURVE_NUMBER
          WRITE(1,107)CURVE_NUMBER
107   FORMAT(///,10X,'CURVE NUMBER FOR THE WATERSHED:',I3)
      STOP
      END

          SUBROUTINE CURVE_NUM(C,S,L)
          INTEGER C,S,L
          IF((S.EQ.1).AND.(L.EQ.1))THEN
             C=72
          ELSEIF((S.EQ.1).AND.(L.EQ.2))THEN
             C=62
          ELSEIF((S.EQ.1).AND.(L.EQ.3))THEN
             C=68
          ELSEIF((S.EQ.1).AND.(L.EQ.4))THEN
             C=39
          ELSEIF((S.EQ.1).AND.(L.EQ.5))THEN
             C=30
          ELSEIF((S.EQ.1).AND.(L.EQ.6))THEN
             C=45
          ELSEIF((S.EQ.1).AND.(L.EQ.7))THEN
             C=25
          ELSEIF((S.EQ.1).AND.(L.EQ.8))THEN
             C=39
          ELSEIF((S.EQ.1).AND.(L.EQ.9))THEN
             C=49
          ELSEIF((S.EQ.1).AND.(L.EQ.10))THEN
             C=89
          ELSEIF((S.EQ.1).AND.(L.EQ.11))THEN
             C=81
          ELSEIF((S.EQ.1).AND.(L.EQ.12))THEN
```

```
    C=77
ELSEIF((S.EQ.1).AND.(L.EQ.13))THEN
    C=61
ELSEIF((S.EQ.1).AND.(L.EQ.14))THEN
    C=57
ELSEIF((S.EQ.1).AND.(L.EQ.15))THEN
    C=54
ELSEIF((S.EQ.1).AND.(L.EQ.16))THEN
    C=51
ELSEIF((S.EQ.1).AND.(L.EQ.17))THEN
    C=98
ELSEIF((S.EQ.1).AND.(L.EQ.18))THEN
     C=98
ELSEIF((S.EQ.1).AND.(L.EQ.19))THEN
     C=76
ELSEIF((S.EQ.1).AND.(L.EQ.20))THEN
    C=72
ELSEIF((S.EQ.2).AND.(L.EQ.1))THEN
    C=81
ELSEIF((S.EQ.2).AND.(L.EQ.2))THEN
    C=71
ELSEIF((S.EQ.2).AND.(L.EQ.3))THEN
    C=79
ELSEIF((S.EQ.2).AND.(L.EQ.4))THEN
    C=61
ELSEIF((S.EQ.2).AND.(L.EQ.5))THEN
    C=58
ELSEIF((S.EQ.2).AND.(L.EQ.6))THEN
     C=66
ELSEIF((S.EQ.2).AND.(L.EQ.7))THEN
    C=55
ELSEIF((S.EQ.2).AND.(L.EQ.8))THEN
    C=61
ELSEIF((S.EQ.2).AND.(L.EQ.9))THEN
    C=69
ELSEIF((S.EQ.2).AND.(L.EQ.10))THEN
    C=92
ELSEIF((S.EQ.2).AND.(L.EQ.11))THEN
    C=88
ELSEIF((S.EQ.2).AND.(L.EQ.12))THEN
    C=85
ELSEIF((S.EQ.2).AND.(L.EQ.13))THEN
    C=75
ELSEIF((S.EQ.2).AND.(L.EQ.14))THEN
    C=72
ELSEIF((S.EQ.2).AND.(L.EQ.15))THEN
    C=70
ELSEIF((S.EQ.2).AND.(L.EQ.16))THEN
    C=68
ELSEIF((S.EQ.2).AND.(L.EQ.17))THEN
    C=98
ELSEIF((S.EQ.2).AND.(L.EQ.18))THEN
    C=98
ELSEIF((S.EQ.2).AND.(L.EQ.19))THEN
    C=85
ELSEIF((S.EQ.2).AND.(L.EQ.20))THEN
```

```
      C=82
ELSEIF((S.EQ.3).AND.(L.EQ.1))THEN
      C=88
ELSEIF((S.EQ.3).AND.(L.EQ.2))THEN
       C=78
ELSEIF((S.EQ.3).AND.(L.EQ.3))THEN
      C=86
ELSEIF((S.EQ.3).AND.(L.EQ.4))THEN
      C=74
ELSEIF((S.EQ.3).AND.(L.EQ.5))THEN
      C=71
ELSEIF((S.EQ.3).AND.(L.EQ.6))THEN
      C=77
ELSEIF((S.EQ.3).AND.(L.EQ.7))THEN
      C=70
ELSEIF((S.EQ.3).AND.(L.EQ.8))THEN
      C=74
ELSEIF((S.EQ.3).AND.(L.EQ.9))THEN
      C=79
ELSEIF((S.EQ.3).AND.(L.EQ.10))THEN
      C=94
ELSEIF((S.EQ.3).AND.(L.EQ.11))THEN
      C=91
ELSEIF((S.EQ.3).AND.(L.EQ.12))THEN
      C=90
ELSEIF((S.EQ.3).AND.(L.EQ.13))THEN
      C=83
ELSEIF((S.EQ.3).AND.(L.EQ.14))THEN
      C=81
ELSEIF((S.EQ.3).AND.(L.EQ.15))THEN
      C=80
ELSEIF((S.EQ.3).AND.(L.EQ.16))THEN
      C=79
ELSEIF((S.EQ.3).AND.(L.EQ.17))THEN
      C=98
ELSEIF((S.EQ.3).AND.(L.EQ.18))THEN
       C=98
ELSEIF((S.EQ.3).AND.(L.EQ.19))THEN
      C=89
ELSEIF((S.EQ.3).AND.(L.EQ.20))THEN
      C=87
ELSEIF((S.EQ.4).AND.(L.EQ.1))THEN
       C=91
ELSEIF((S.EQ.4).AND.(L.EQ.2))THEN
       C=81
ELSEIF((S.EQ.4).AND.(L.EQ.3))THEN
      C=89
ELSEIF((S.EQ.4).AND.(L.EQ.4))THEN
      C=80
ELSEIF((S.EQ.4).AND.(L.EQ.5))THEN
      C=78
ELSEIF((S.EQ.4).AND.(L.EQ.6))THEN
      C=83
ELSEIF((S.EQ.4).AND.(L.EQ.7))THEN
      C=77
ELSEIF((S.EQ.4).AND.(L.EQ.8))THEN
```

```
     C=80
ELSEIF((S.EQ.4).AND.(L.EQ.9))THEN
     C=84
ELSEIF((S.EQ.4).AND.(L.EQ.10))THEN
      C=95
ELSEIF((S.EQ.4).AND.(L.EQ.11))THEN
      C=93
ELSEIF((S.EQ.4).AND.(L.EQ.12))THEN
     C=92
ELSEIF((S.EQ.4).AND.(L.EQ.13))THEN
     C=87
ELSEIF((S.EQ.4).AND.(L.EQ.14))THEN
     C=86
ELSEIF((S.EQ.4).AND.(L.EQ.15))THEN
     C=85
ELSEIF((S.EQ.4).AND.(L.EQ.16))THEN
     C=84
ELSEIF((S.EQ.4).AND.(L.EQ.17))THEN
     C=98
ELSEIF((S.EQ.4).AND.(L.EQ.18))THEN
      C=98
ELSEIF((S.EQ.4).AND.(L.EQ.19))THEN
     C=91
ELSEIF((S.EQ.4).AND.(L.EQ.20))THEN
     C=89
              ENDIF
RETURN
END
```

MUS_HYDRO_EXPREC_KNK

```
C    ******************************************************************
C
C      PROGRAM MUS_IUH_KNK.FOR
C
C     THIS PROGRAM ROUTES THE RUNOFF USING THE
C          MUSKINGUM METHOD TO PRODUCE A DIRECT RUNOFF HYDROGRAPH AND USES THE
           MUSKINGUM-CUNGE
C      METHOD TO DETERMINE THE REQUIRED PARAMETERS
C      STORAGE CONSTANT K AND WEDGE CONSTANT X
C
C    ******************************************************************
C
C           WRITTEN BY: KHALID KHAN
C      DATED : 07/26/01
C
C    ******************************************************************
C      THIS SECTION IS FOR INPUT DATA
C
      INTEGER  Z, J,SIZE
      REAL T,C1,K,C0,C2,SUM,Q(500),I(500)
C           REAL QT(500),QM(500)
            PRINT*, '*** THE STORAGE CONSTANT K IS CALCULATED AS ***'
            PRINT*, '                                  '
            PRINT*, 'K=DELTA_X/C   WHERE'
            PRINT*, '            DELTA_X=REACH LENGTH'
            PRINT*, '            C=FLOOD WAVE CELERITY GIVEN BY C=M*V'
            PRINT*, '            M=CONSTANT WITH VALUE 5/3'
            PRINT*, '            V=AVERAGE VELOCITY AT BANKFUL DISCHARGE'
            PRINT*, '                                       '
      PRINT*, '*** IF THE ABOVE MENTIONED METHOD IS NOT EMPLOYED THEN'
            PRINT*, '    K CAN BE APPROXIMATED AS EQUAL TO THE TRAVEL TIME'
            PRINT*, '    IN THE REACH OR THE TIME OF CONCENTRATION ***'
            PRINT*, '                                  '
            PRINT*, '*** ENTER STORAGE CONSTANT---K IN MINUTES***'
      READ*, K
            PRINT*, '*** THE WEDGE PARAMETER X IS ESIMATED AS ***'
            PRINT*, 'X=0.5(1-(Q0/(S0*C*DELTA_X))) WHERE'
            PRINT*, '                      Q0=DISCHARGE PER UNIT '
            PRINT*, '                      WIDTH OF THE CHANNEL AT'
            PRINT*, '                      PEAK FLOW RATE'
            PRINT*, '                      S0=SLOPE OF CHANNEL'
            PRINT*, '                      C=FLOOD WAVE CELERITY'
            PRINT*, '                      DELTA_X=REACH LENGTH'
            PRINT*, '                                    '
            PRINT*, '*** IF THE ABOVE MENTIONED METHOD IS NOT EMPLOYED THEN'
            PRINT*, '    PUT X = 0.25 ***'
            PRINT*, '                                  '
            PRINT*, '*** ENTER WEDGE PARAMETER----X ***'
```

```
        READ*, X
      PRINT*, '*** ENTER THE INITIAL OUTFLOW (CFS) ***'
      READ*, Q(0)
        PRINT*, '*** ENTER THE GRID SIZE ***'
        READ*, SIZE
      OPEN (10,STATUS='OLD',FILE='EX_PREC.TXT')
      SUM=0.0
      READ (10,*) J
      READ (10,*) T
      DO 10 Z=1,J
      READ (10,*) I(Z)
      I(Z)=I(Z)*(SIZE**2)*(3.28**2)/(12.0*60.0*T)
      SUM=SUM+I(Z)
10    CONTINUE
      IF (SUM.EQ.0.0) THEN
      PRINT*, 'NO DATA VALUES IN THE EX_PREC.TXT FILE'
      END IF
C     QT(0)=Q(0)/2.0
C
C        THIS SECTION IS TO CALCULATE THE COEFFICIENTS
C
      C0=(0.5*T-K*X)/(K*(1-X)+0.5*T)
      C1=(0.5*T+K*X)/(K*(1-X)+0.5*T)
        C2=(K*(1-X)-0.5*T)/(K*(1-X)+0.5*T)
C
C        THIS SECTION IS TO ROUTE AND PRINT OUT
C     THE RESULTS
C
      DO 20 Z=1,J
      Q(Z)=C0*I(Z)+C1*I(Z-1)+C2*Q(Z-1)
C     QM(Z)=C0*I(Z+1)+C1*Q(Z)
C     QT(Z+1)=(QM(Z)+Q(Z))/2.0
C     QT(1)=(Q(1)+Q(0))/2.0

C        PRINT *,I(Z),Q(Z)
20    CONTINUE
      OPEN (20,FILE='HYDRO.TXT',STATUS='NEW')
      WRITE (20,*)
      WRITE (20,*) '      Time', '       HYDRO'
      WRITE (20,*) '      (min)', '        (cfs)'
      WRITE (20,*)
      TI=0.0
      DO 30 Z=0,J
      WRITE (20,1) TI, Q(Z)
1     FORMAT (2X,F10.2,3X,F10.2)
      TI=TI+T
30    CONTINUE
      Z=J
      TI=TI-T
40    TI=TI+T
      I(Z+1)=0.0
      I(Z+2)=0.0
      Q(Z+1)=C0*I(Z+1)+C1*I(Z)+C2*Q(Z)
C     QT(Z+2)=(Q(Z)+Q(Z+1))/2.0
      IF ((Q(Z+1).LT.0.01).OR.(TI.GE.5000)) THEN
      GOTO 50
```

```
      ENDIF
      WRITE (20,2) TI, Q(Z+1)
2     FORMAT (2X,F10.2,3X,F10.2)
      Z=Z+1
      GOTO 40
50    STOP
      END
```

PREC_REAL_KNK

```
C   ********************************************************************
C
C       PROGRAM PREC_REAL_KNK.FOR
C
C            THIS PROGRAM CREATES THE PRECIPITATION FILE
C            WITH REAL VALUES OF PRECIPITATION. THE AREAS
C            ARE AS THEY ARE DEFINED IN THE MASK FILE
C
C   ********************************************************************
C
C            WRITTEN BY: KHALID KHAN
C       DATED : 07/26/01
C
C   ********************************************************************

      IMPLICIT INTEGER*2 (A-Z)
      CHARACTER*80 DIFILE
      CHARACTER*80 MAFILE
      LOGICAL DONE,ACTIV
      INTEGER*2 DIR(20000,3)
            REAL*4 MASK(20000,3)
      COMMON DIR,MASK
      PRINT 1
1     FORMAT(/,'*** ENTER LENGTH AND WIDTH OF FILE ***')
      READ(*,*)NL,NS
      PRINT 2
2     FORMAT('*** ENTER DIRECTION FILE ***')
      READ (5,1000)DIFILE
      PRINT 3
3     FORMAT('*** ENTER MASK FILE ***')
      READ (5,1000)MAFILE
1000  FORMAT(A80)
C-- DFILE IS THE SDIR FILE THAT IS MADE BY DOSDIR, I*2
      DFILE=13
C-- MFILE IS THE STARTER FILE,0 FOR MASK,-1 FOR NO LABEL YET,
C    AND A NUMBER WHERE THE USER WISHES A WATERSHED TO TERMINATE
      MFILE=12
C
C     This section is for opening files under UNIX and DOS
C
      OPEN(UNIT=DFILE,STATUS='OLD',RECL=NS*2,
     *   FORM='UNFORMATTED',ACCESS='DIRECT',
     *   FILE=DIFILE)
      OPEN(UNIT=MFILE,STATUS='OLD',FORM='UNFORMATTED',
     *   ACCESS='DIRECT',FILE=MAFILE,RECL=NS*4)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      UPDOWN=-1
```

```
      PASS=0
33    I1=1
      I2=2
      I3=3
      UPDOWN=-UPDOWN
      DONE=.TRUE.
      PASS=PASS+1
      PRINT *,'PASS',PASS
      DO 4 II=1,NS+2
      INDEX=1
      IF(UPDOWN.EQ.-1)INDEX=3
4     MASK(II,INDEX)=0
      DO 5 I=1,3
      MASK(1,I)=0
5     MASK(NS+2,I)=0
      INDEX2=0
      IF(UPDOWN.EQ.-1)INDEX2=NL-2
      INDEX1=1
      IF(UPDOWN.EQ.-1)INDEX1=0
      DO 6 I=1,2
      READ(DFILE,REC=I+INDEX2)(DIR(II,I+INDEX1),II=2,NS+1)
6     READ(MFILE,REC=I+INDEX2)(MASK(II,I+INDEX1),II=2,NS+1)
      DO 10 I=1,NL
15    ACTIV=.FALSE.
      DO 20 J=2,NS+1
      IF(MASK(J,I2).NE.-1)GOTO 20
      DIRX=DIR(J,I2)
      IF(DIRX.NE.0) GOTO 16
      MASK(J,I2) = 0
      ACTIV = .TRUE.
      GOTO 20
16    IF(MASK(J+1,I1).LT.0.OR.DIRX.NE.1)GOTO 21
      MASK(J,I2)=MASK(J+1,I1)
      ACTIV=.TRUE.
      GOTO 20
21    IF(MASK(J+1,I2).LT.0.OR.DIRX.NE.2)GOTO 22
      MASK(J,I2)=MASK(J+1,I2)
      ACTIV=.TRUE.
      GOTO 20
22    IF(MASK(J+1,I3).LT.0.OR.DIRX.NE.4)GOTO 23
      MASK(J,I2)=MASK(J+1,I3)
      ACTIV=.TRUE.
      GOTO 20
23    IF(MASK(J,I3).LT.0.OR.DIRX.NE.8)GOTO 24
      MASK(J,I2)=MASK(J,I3)
      ACTIV=.TRUE.
      GOTO 20
24    IF(MASK(J-1,I3).LT.0.OR.DIRX.NE.16)GOTO 25
      MASK(J,I2)=MASK(J-1,I3)
      ACTIV=.TRUE.
      GOTO 20
25    IF(MASK(J-1,I2).LT.0.OR.DIRX.NE.32)GOTO 26
      MASK(J,I2)=MASK(J-1,I2)
      ACTIV=.TRUE.
      GOTO 20
26    IF(MASK(J-1,I1).LT.0.OR.DIRX.NE.64)GOTO 27
```

```
     MASK(J,I2)=MASK(J-1,I1)
     ACTIV=.TRUE.
     GOTO 20
 27  IF(MASK(J,I1).LT.0.OR.DIRX.NE.128)GOTO 20
     MASK(J,I2)=MASK(J,I1)
     ACTIV=.TRUE.
     GOTO 20
 20  IF(ACTIV)DONE=.FALSE.
     IF(ACTIV)GOTO 15
     INDEX=I
     IF(UPDOWN.EQ.-1)INDEX=NL-I+1
     WRITE(MFILE,REC=INDEX)(MASK(II,I2),II=2,NS+1)
     IF(I.EQ.NL)GOTO 10
     IF(UPDOWN.EQ.-1)GOTO 18
     ITEMP=I1
     I1=I2
     I2=I3
     I3=ITEMP
     IF(I.NE.NL-1)GOTO 65
     DO 64 II=1,NS+2
 64  MASK(II,I3)=0
     GOTO 10
 65  READ(MFILE,REC=I+2)(MASK(II,I3),II=2,NS+1)
     READ(DFILE,REC=I+2)(DIR(II,I3),II=2,NS+1)
     GOTO 10
C--DOING A BOTTOM TO TOP PASS
 18  ITEMP=I3
     I3=I2
     I2=I1
     I1=ITEMP
     IF(I.NE.NL-1)GOTO 19
     DO 17 II=1,NS+2
 17  MASK(II,I1)=0
     GOTO 10
 19  READ(MFILE,REC= NL-I-1)(MASK(II,I1),II=2,NS+1)
     READ(DFILE,REC=NL-I-1)(DIR(II,I1),II=2,NS+1)
 10  CONTINUE
     IF(.NOT.DONE)GOTO 33
     STOP
     END
```

APPENDIX B

APPENDIX B

FORTRAN CODES FOR THE PROGRAMS FROM THE PREVIOUS STUDIES USED IN THIS STUDY

DIR

```
C  PROGRAM DIRECT.FOR
      IMPLICIT INTEGER*2 (A-Z)
      CHARACTER*80 DIFILE
      CHARACTER*80 ELFILE
      LOGICAL ACTIVE(20000),ACTIV,GOGAIN
      INTEGER*2 LEVEL(20000,3)
      DIMENSION DIR(20000),SDIR(20000,3),SELECT(256)
      EQUIVALENCE (SDIR(1,1),LEVEL(1,1))
      COMMON ACTIVE,LEVEL,DIR
      DATA SELECT/  0,  1,  2,  2,  4,  1,  2,  2,  8,  1,
     *  8,  2,  8,  4,  4,  2, 16, 16, 16,  2, 16,  4,  4,
     *  2,  8,  8,  8,  8,  8,  8,  8,  4, 32,  1,  2,  2,
     *  4,  4,  2,  2, 32,  8,  8,  2,  8,  8,  4,  4, 32,
     * 32, 32, 32, 16, 32,  4,  2, 16, 16, 16, 16,  8, 16,
     *  8,  8, 64, 64, 64,  1, 64,  1,  2,  2, 64, 64,  8,
     *  2,  8,  8,  4,  2, 16, 64, 64,  2, 16, 64,  2,  2,
     * 16,  8,  8,  8,  8,  8,  8,  4, 32, 64, 32,  1, 32,
     * 32, 32,  2, 32, 32, 32,  2, 32,  8,  4,  4, 32, 32,
     * 32, 32, 32, 32, 32, 32, 32, 32, 16, 16, 16, 16,  8,
     *  8,128,128,128,  1,  4,  1,  2,  2,128,128,  2,  1,
     *  8,  4,  4,  2, 16,128,  2,  1,  4,128,  2,  1,  8,
     *128,  8,  1,  8,  8,  4,  2, 32,128,  1,  1,128,128,
     *  2,  1, 32,128, 32,  1,  8,128,  4,  2, 32, 32, 32,
     *  1, 32,128, 32,  1, 16, 16, 16,  1, 16, 16,  8,  4,
     *128,128,128,128,128,128,  2,  1,128,128,128,  1,128,
     *128,  4,  2, 64,128,128,  1,128,128,128,  1,  8,128,
     *  8,  1,  8,  8,  8,  2, 64,128, 64,128, 64,128, 64,
     *128, 32, 64, 64,128, 64, 64, 64,  1, 32, 64, 64,128,
     * 64, 64, 64,128, 32, 32, 32, 64, 32, 32, 16,128/
      I1=1
      I2=2
      I3=3
      PRINT 1
1     FORMAT(/,'*** ENTER LENGTH AND WIDTH OF FILE ***')
C-- LFILE IS THE I*2 ELEVATION LEVELS
      LFILE=11
C-- SFILE IS THE SELECTED DIR FILE THAT IS MADE NEXT, I*2
      SFILE=15
      READ(*,*)NL,NS
      PRINT 2
2     FORMAT('*** ENTER ELEVATION FILE ***')
      READ(5,1000)ELFILE
      PRINT 3
3     FORMAT('*** ENTER DIRECTION FILE ***')
      READ(5,1000)DIFILE
```

```
1000  FORMAT(A80)
C
C     This section is for opening files under UNIX and DOS
C
      OPEN(UNIT=LFILE,FILE=ELFILE,STATUS='OLD',FORM='UNFORMATTED',
     * ACCESS='DIRECT',RECL=NS*2)
      OPEN(UNIT=SFILE,FILE=DIFILE,STATUS='NEW',FORM='UNFORMATTED',
     * ACCESS='DIRECT',RECL=NS*2)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C--  DIR CODES AS...  7  8  1
C                     6     2
C                     5  4  3
14    DO 5 I=1,NS+2
      DIR(I)=0
5     LEVEL(I,1)=0
      LEVEL(1,2)=0
      LEVEL(NS+2,2)=0
      LEVEL(1,3)=0
      LEVEL(NS+2,3)=0
      READ (LFILE,REC=1)(LEVEL(II,I2),II=2,NS+1)
      WRITE(1,*)LEVEL(2,I2),LEVEL(3,I2)
      DO 10 I=2,NL+1
      IF (I.LE.NL)GOTO 15
      DO 13 II=1,NS
 13   LEVEL(II,I3)=0
      GOTO 17
 15   READ(LFILE,REC=I)(LEVEL(II,I3),II=2,NS+1)
      WRITE (1,*)LEVEL(2,I3),LEVEL(3,I3)
C-- PROCESS FIRST AND LAST SAMPLES IN THE LINE
 17   DO 20 J=2,NS+1
      DIR(J)=0
      IF(LEVEL(J,I2).EQ.0)GOTO 20
      DIR(J)=THEDIR(LEVEL(J,I2),LEVEL(J+1,I1),LEVEL(J+1,I2),
     *           LEVEL(J+1,I3),LEVEL(J,I3),LEVEL(J-1,I3),
     *           LEVEL(J-1,I2),LEVEL(J-1,I1),LEVEL(J,I1))
      WRITE(1,*)DIR(1),DIR(2),DIR(3),DIR(4)
 20   CONTINUE
      WRITE(SFILE,REC=I-1)(DIR(II),II=2,NS+1)
      ITEMP=I1
      I1=I2
      I2=I3
      I3=ITEMP
 10   CONTINUE
C-- NOW MAKE A PASS RESOLVING NON-FLATS WITH MORE THAN ONE DOWN LINK
      DO 30 I=1,NL
      READ(SFILE,REC=I)(DIR(J),J=1,NS)
      DO 31 J=1,NS
      IF(DIR(J).LT.0)GOTO 31
      DIR(J)=SELECT(DIR(J)+1)
 31   CONTINUE
 30   WRITE(SFILE,REC=I)(DIR(J),J=1,NS)
C-- NOW ITERATE ON THE SFILE, LINKING IN THE FLATS.
 41   DO 40 I=2,NL-1
 40   ACTIVE(I)=.TRUE.
      ACTIVE(1)=.FALSE.
```

```
      ACTIVE(NL)=.FALSE.
      I1=1
      I2=2
      I3=3
      FIRSTL=2
      LASTL=NL-1
      PASS=0
C     PROCESS THE DOWNWARD PASS
C
 35   ACTIV=.FALSE.
      READ(SFILE,REC=FIRSTL-1)(SDIR(J,I1),J=1,NS)
      READ(SFILE,REC=FIRSTL)(SDIR(J,I2),J=1,NS)
      READ(SFILE,REC=FIRSTL+1)(SDIR(J,I3),J=1,NS)
      PASS=PASS+1
      PRINT *,'DOWNWARD PASS',PASS,'  FIRSTL',FIRSTL,'  LASTL',LASTL
      I=FIRSTL
 42   ACTIVE(I)=.FALSE.
 51   GOGAIN = .FALSE.
      DO 50 J=2,NS-1
      DIR(J)=SDIR(J,I2)
 50   IF(SDIR(J,I2).LT.0)DIR(J)=LINK(SDIR(J,I2),ACTIVE(I),SDIR(J+1,I1),
     *   SDIR(J+1,I2),SDIR(J+1,I3),SDIR(J,I3),
     *   SDIR(J-1,I3),SDIR(J-1,I2),SDIR(J-1,I1),
     *   SDIR(J,I1),SELECT,ACTIV,GOGAIN)
      IF (GOGAIN) GOTO 51
      WRITE(SFILE,REC=I)SDIR(1,I2),(DIR(K),K=2,NS-1),SDIR(NS,I2)
C-- ROTATE TO THE NEXT LINE
 45   I=I+1
      IF(I.GT.LASTL-1)GOTO 60
      ITEMP=I1
      I1=I2
      I2=I3
      I3=ITEMP
      IF(.NOT.ACTIVE(I).AND..NOT.ACTIVE(I+1)
     *    .AND..NOT.ACTIVE(I+2))GOTO 45
      READ(SFILE,REC=I+1)(SDIR(K,I3),K=1,NS)
      IF(.NOT.ACTIVE(I))GOTO 45
      GOTO 42
C-- DONE WITH THIS ITERATION,  UPDATE FIRSTL AND LASTL AND GO AGAIN
 60   DO 70 I=FIRSTL,LASTL
      IF(ACTIVE(I))GOTO 73
 70   CONTINUE
C-- ALL DONE
      GOTO 100
 73   IF (ACTIV)GOTO 75
      PRINT *,'COULD NOT SOLVE FOR ALL CELLS'
      GOTO 100
 75   FIRSTL=I
      DO 80 I=LASTL,FIRSTL,-1
      IF(ACTIVE(I))GOTO 85
 80   CONTINUE
 85   LASTL=I
C
C     PROCESS THE UPWARD PASS
C
 350  ACTIV=.FALSE.
```

```
      READ(SFILE,REC=LASTL+1)(SDIR(J,I3),J=1,NS)
      READ(SFILE,REC=LASTL)(SDIR(J,I2),J=1,NS)
      READ(SFILE,REC=LASTL-1)(SDIR(J,I1),J=1,NS)
      PASS=PASS+1
      PRINT *,'UPWARD PASS',PASS,'  FIRSTL',FIRSTL,'  LASTL',LASTL
      I=LASTL
 420  ACTIVE(I)=.FALSE.
 510  GOGAIN = .FALSE.
      DO 500 J=2,NS-1
      DIR(J)=SDIR(J,I2)
 500  IF(SDIR(J,I2).LT.0)DIR(J)=LINK(SDIR(J,I2),ACTIVE(I),SDIR(J+1,I1),
     *   SDIR(J+1,I2),SDIR(J+1,I3),SDIR(J,I3),
     *   SDIR(J-1,I3),SDIR(J-1,I2),SDIR(J-1,I1),
     *   SDIR(J,I1),SELECT,ACTIV,GOGAIN)
      IF (GOGAIN) GOTO 510
      WRITE(SFILE,REC=I)SDIR(1,I2),(DIR(K),K=2,NS-1),SDIR(NS,I2)
C-- ROTATE TO THE NEXT LINE
 450  I=I-1
      IF(I.LT.FIRSTL-1)GOTO 600
      ITEMP=I3
      I3=I2
      I2=I1
      I1=ITEMP
      IM1=MAX(I-1,1)
      IM2=MAX(I-2,1)
      IF(.NOT.ACTIVE(I).AND..NOT.ACTIVE(IM1)
     *    .AND..NOT.ACTIVE(IM2))GOTO 450
      READ(SFILE,REC=I-1)(SDIR(K,I1),K=1,NS)
      IF(.NOT.ACTIVE(I))GOTO 450
      GOTO 420
C-- DONE WITH THIS ITERATION,  UPDATE FIRSTL AND LASTL AND GO AGAIN
 600  DO 700 I=LASTL,FIRSTL,-1
      IF(ACTIVE(I))GOTO 730
 700  CONTINUE
C-- ALL DONE
      GOTO 100
 730  IF (ACTIV)GOTO 750
      PRINT *,'COULD NOT SOLVE FOR ALL CELLS'
      GOTO 100
 750  LASTL=I
      DO 800 I=FIRSTL,LASTL
      IF(ACTIVE(I))GOTO 850
 800  CONTINUE
 850  FIRSTL=I
C
C     END OF UPWARD PROCESS
C
      GOTO 35
 100  CONTINUE
      STOP
      END
C
C
      FUNCTION THEDIR(MID,N1,N2,N3,N4,N5,N6,N7,N8)
      IMPLICIT INTEGER*2 (A-Z)
      REAL N(8),MAXDRO
```

```
C-- RETURN A <0 MASK IF THE PATHS ARE FLAT.
      THEDIR=0
      N(1)=(MID-N1)/1.414
      N(2)= MID-N2
      N(3)=(MID-N3)/1.414
      N(4)= MID-N4
      N(5)=(MID-N5)/1.414
      N(6)= MID-N6
      N(7)=(MID-N7)/1.414
      N(8)= MID-N8
      MAXDRO=MAX(N(1),N(2),N(3),N(4),N(5),N(6),N(7),N(8))
      DO 10 I=1,8
 10   IF (N(I).EQ.MAXDRO)THEDIR=THEDIR+2**(I-1)
      IF(MAXDRO.EQ.0)THEDIR=-THEDIR
c-- A PIT WILL BE A -300
      IF(MAXDRO.LT.0)THEDIR=-300
      RETURN
      END
C
C
      FUNCTION LINK(CENTER,ACTIVE,D1,D2,D3,D4,D5,D6,D7,D8,SELECT
     * ,ACTIV,GOGAIN)
      IMPLICIT INTEGER*2(A-Z)
      LOGICAL ACTIVE,C(8),ACTIV,GOGAIN
      DIMENSION SELECT(256),BITMAS(8)
      DATA BITMAS/1,2,4,8,16,32,64,128/
      LINK=CENTER
C-- CHECK IF ITS A PIT
      IF(LINK.EQ.-300)GOTO 100
      CWORK=-CENTER
      DO 5 I=8,1,-1
      C(I)=.FALSE.
      IF(CWORK-BITMAS(I).LT.0)GOTO 5
      CWORK=CWORK-BITMAS(I)
      C(I)=.TRUE.
 5    CONTINUE
C-- CHECK FOR DOWNSTREAM LINKS
      OUTFLO=0
      IF(D1.NE.16.AND.D1.GT.0.AND.C(1))OUTFLO=OUTFLO+1
      IF(D2.NE.32.AND.D2.GT.0.AND.C(2))OUTFLO=OUTFLO+2
      IF(D3.NE.64.AND.D3.GT.0.AND.C(3))OUTFLO=OUTFLO+4
      IF(D4.NE.128.AND.D4.GT.0.AND.C(4))OUTFLO=OUTFLO+8
      IF(D5.NE.1.AND.D5.GT.0.AND.C(5))OUTFLO=OUTFLO+16
      IF(D6.NE.2.AND.D6.GT.0.AND.C(6))OUTFLO=OUTFLO+32
      IF(D7.NE.4.AND.D7.GT.0.AND.C(7))OUTFLO=OUTFLO+64
      IF(D8.NE.8.AND.D8.GT.0.AND.C(8))OUTFLO=OUTFLO+128
      IF(OUTFLO.EQ.0)GOTO 10
      CENTER=SELECT(OUTFLO+1)
      LINK=CENTER
      ACTIV=.TRUE.
      GOGAIN=.TRUE.
      GOTO 100
 10   ACTIVE=.TRUE.
 100  CONTINUE
      RETURN
      END
```

WTRSHED

```
C  PROGRAM WTRSHED.FOR
      IMPLICIT INTEGER*2 (A-Z)
      CHARACTER*80 DIFILE
      CHARACTER*80 MAFILE
      LOGICAL DONE,ACTIV
      DIMENSION DIR(20000,3),MASK(20000,3)
      COMMON DIR,MASK
      PRINT 1
1     FORMAT(/,'*** ENTER LENGTH AND WIDTH OF FILE ***')
      READ(*,*)NL,NS
      PRINT 2
2     FORMAT('*** ENTER DIRECTION FILE ***')
      READ (5,1000)DIFILE
      PRINT 3
3     FORMAT('*** ENTER MASK FILE ***')
      READ (5,1000)MAFILE
1000  FORMAT(A80)
C-- DFILE IS THE SDIR FILE THAT IS MADE BY DOSDIR, I*2
      DFILE=13
C-- MFILE IS THE STARTER FILE,0 FOR MASK,-1 FOR NO LABEL YET,
C    AND A NUMBER WHERE THE USER WISHES A WATERSHED TO TERMINATE
      MFILE=12
C
C     This section is for opening files under UNIX and DOS
C
      OPEN(UNIT=DFILE,STATUS='OLD',RECL=NS*2,
     *   FORM='UNFORMATTED',ACCESS='DIRECT',
     *   FILE=DIFILE)
      OPEN(UNIT=MFILE,STATUS='OLD',FORM='UNFORMATTED',
     *   ACCESS='DIRECT',FILE=MAFILE,RECL=NS*2)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      UPDOWN=-1
      PASS=0
 33   I1=1
      I2=2
      I3=3
      UPDOWN=-UPDOWN
      DONE=.TRUE.
      PASS=PASS+1
      PRINT *,'PASS',PASS
      DO 4 II=1,NS+2
      INDEX=1
      IF(UPDOWN.EQ.-1)INDEX=3
 4    MASK(II,INDEX)=0
      DO 5 I=1,3
      MASK(1,I)=0
 5    MASK(NS+2,I)=0
      INDEX2=0
      IF(UPDOWN.EQ.-1)INDEX2=NL-2
      INDEX1=1
      IF(UPDOWN.EQ.-1)INDEX1=0
```

```
      DO 6 I=1,2
      READ(DFILE,REC=I+INDEX2)(DIR(II,I+INDEX1),II=2,NS+1)
6     READ(MFILE,REC=I+INDEX2)(MASK(II,I+INDEX1),II=2,NS+1)
      DO 10 I=1,NL
15    ACTIV=.FALSE.
      DO 20 J=2,NS+1
      IF(MASK(J,I2).NE.-1)GOTO 20
      DIRX=DIR(J,I2)
      IF(DIRX.NE.0) GOTO 16
      MASK(J,I2) = 0
      ACTIV = .TRUE.
      GOTO 20
16    IF(MASK(J+1,I1).LT.0.OR.DIRX.NE.1)GOTO 21
      MASK(J,I2)=MASK(J+1,I1)
      ACTIV=.TRUE.
      GOTO 20
21    IF(MASK(J+1,I2).LT.0.OR.DIRX.NE.2)GOTO 22
      MASK(J,I2)=MASK(J+1,I2)
      ACTIV=.TRUE.
      GOTO 20
22    IF(MASK(J+1,I3).LT.0.OR.DIRX.NE.4)GOTO 23
      MASK(J,I2)=MASK(J+1,I3)
      ACTIV=.TRUE.
      GOTO 20
23    IF(MASK(J,I3).LT.0.OR.DIRX.NE.8)GOTO 24
      MASK(J,I2)=MASK(J,I3)
      ACTIV=.TRUE.
      GOTO 20
24    IF(MASK(J-1,I3).LT.0.OR.DIRX.NE.16)GOTO 25
      MASK(J,I2)=MASK(J-1,I3)
      ACTIV=.TRUE.
      GOTO 20
25    IF(MASK(J-1,I2).LT.0.OR.DIRX.NE.32)GOTO 26
      MASK(J,I2)=MASK(J-1,I2)
      ACTIV=.TRUE.
      GOTO 20
26    IF(MASK(J-1,I1).LT.0.OR.DIRX.NE.64)GOTO 27
      MASK(J,I2)=MASK(J-1,I1)
      ACTIV=.TRUE.
      GOTO 20
27    IF(MASK(J,I1).LT.0.OR.DIRX.NE.128)GOTO 20
      MASK(J,I2)=MASK(J,I1)
      ACTIV=.TRUE.
      GOTO 20
20    IF(ACTIV)DONE=.FALSE.
      IF(ACTIV)GOTO 15
      INDEX=I
      IF(UPDOWN.EQ.-1)INDEX=NL-I+1
      WRITE(MFILE,REC=INDEX)(MASK(II,I2),II=2,NS+1)
      IF(I.EQ.NL)GOTO 10
      IF(UPDOWN.EQ.-1)GOTO 18
      ITEMP=I1
      I1=I2
      I2=I3
      I3=ITEMP
      IF(I.NE.NL-1)GOTO 65
```

```
      DO 64 II=1,NS+2
 64   MASK(II,I3)=0
      GOTO 10
 65   READ(MFILE,REC=I+2)(MASK(II,I3),II=2,NS+1)
      READ(DFILE,REC=I+2)(DIR(II,I3),II=2,NS+1)
      GOTO 10
C--DOING A BOTTOM TO TOP PASS
 18   ITEMP=I3
      I3=I2
      I2=I1
      I1=ITEMP
      IF(I.NE.NL-1)GOTO 19
      DO 17 II=1,NS+2
 17   MASK(II,I1)=0
      GOTO 10
 19   READ(MFILE,REC= NL-I-1)(MASK(II,I1),II=2,NS+1)
      READ(DFILE,REC=NL-I-1)(DIR(II,I1),II=2,NS+1)
 10   CONTINUE
      IF(.NOT.DONE)GOTO 33
      STOP
      END
```

APPENDIX C

APPENDIX – C

RESULTS OF SUB WATERSHEDS

Results for sub watershed 1 of Thompson Run watershed

```
            THE CURVE-NUMBER CALCULATION FILE
            ---------------------------------


WATERSHED NUMBER:  1


NUMBER OF CELLS IN THE WATERSHED:     10531



CURVE NUMBER                    NUMBER OF CELLS
------------                    ---------------
     45                              1429
     55                              1623
     68                              1670
     85                               105
     86                              1834
     89                               599
     90                              1065
     92                              2206


       CURVE NUMBER FOR THE WATERSHED: 75
```

Figure C-1 Curve Number file for sub watershed 1 of Thompson Run

```
WATERSHED NUMBER  1
NUMBER OF CELLS =  10530
CURVE NUMBER = 75
AVERAGE EXCESS RAINFALL FOR WATERSHED =   .33
LONGEST FLOWPATH =  8623.52 METERS    SLOPE =   .0157
LENGTH OF MAINSTREAM =  7651.98 METERS    SLOPE =  .0115
TIME OF CONCENTRATION =  1109.17 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
         0           0           3         106         282         196
       116         165         407         323         339         583
       691         452         414         226         259         457
       579         314         162         122         190         219
       272         270         223          92          60          38
        29          23          27          19          36          63
       100          76          71          21          33          35
        35          35          34          32          29          16
        14          23          30          23          25          45
        14           8          18          25          18          18
        23          35          32          46          65          62
        60          49          55          54          53          66
        59          61          60          66          53          41
        58          42          49          56          36          27
        36          37          45          41          52          52
        52          38          46          46          51          32
        43          27          31          19          19          19
        13          13          15          16          13          14
         5           2
         6
```

Figure C-2 Data file for sub watershed 1 of Thompson Run

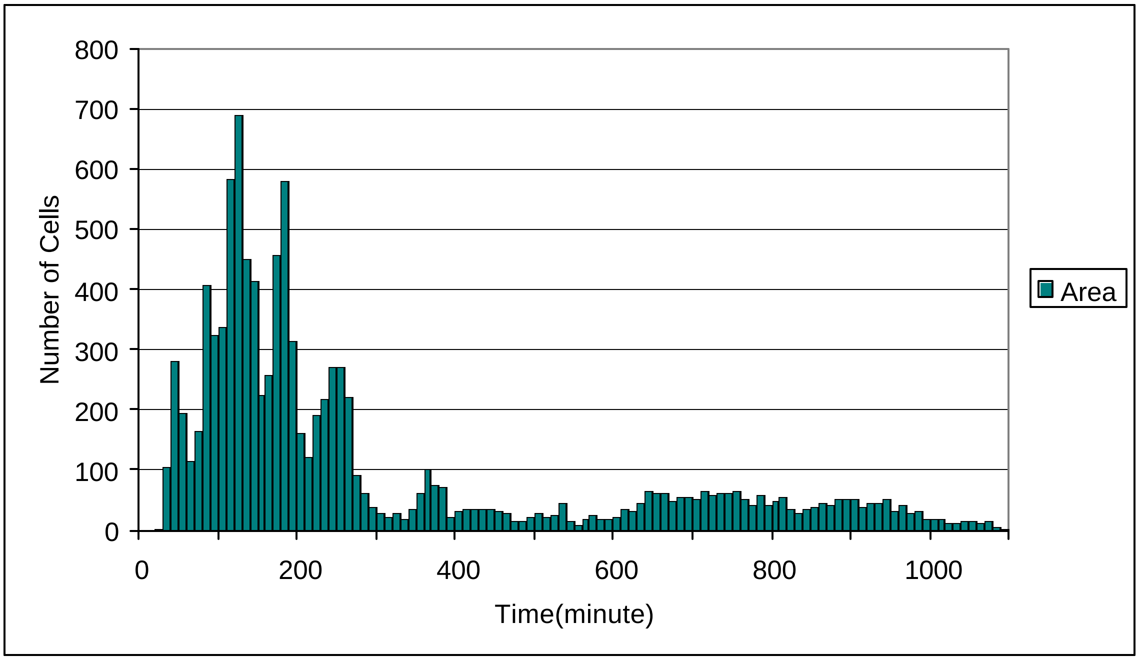

Figure C-3 Time area histogram for sub watershed 1 of Thompson Run

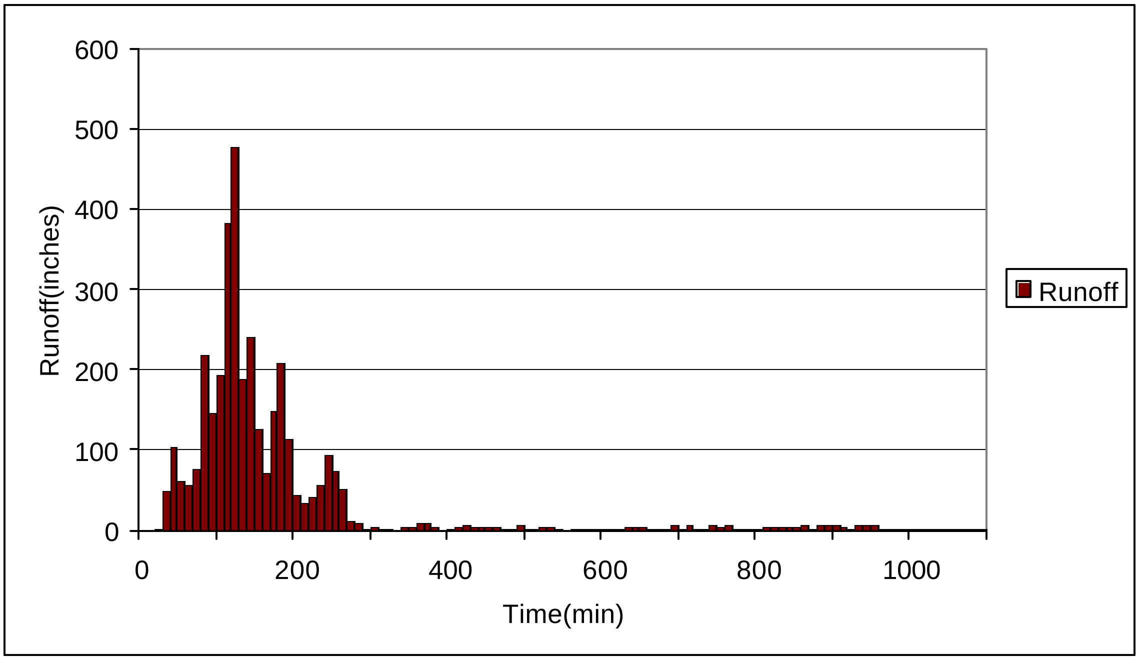

Figure C-4 Runoff time histogram for sub watershed 1 of Thompson Run

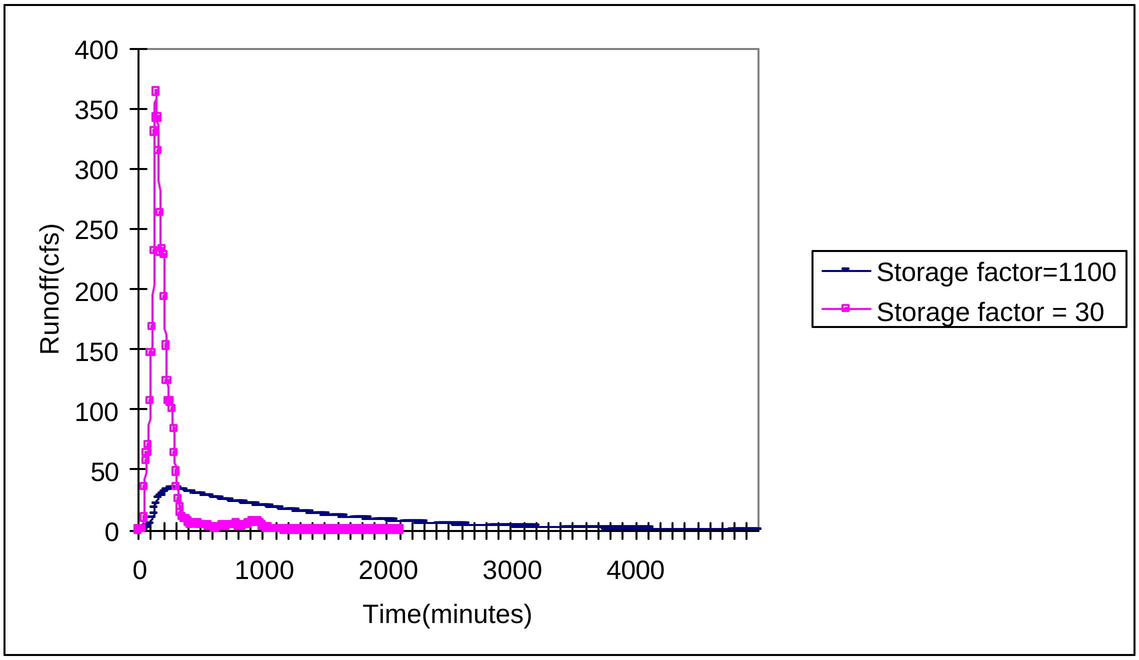

Figure C-5 Direct Runoff Hydrograph for sub watershed 1 of Thompson Run

Results for sub watershed 2 of Thompson Run watershed

```
THE CURVE-NUMBER CALCULATION FILE
---------------------------------


WATERSHED NUMBER:  2


NUMBER OF CELLS IN THE WATERSHED:     12645



CURVE NUMBER                    NUMBER OF CELLS
------------                    ---------------
     45                              1538
     55                              1681
     68                               732
     77                               139
     86                              2592
     89                               696
     90                               409
     92                              4768
     94                                90


     CURVE NUMBER FOR THE WATERSHED: 79
```

Figure C-6 Curve Number file for sub watershed 1 of Thompson Run

```
WATERSHED NUMBER  2


NUMBER OF CELLS =  12644


CURVE NUMBER = 79


AVERAGE EXCESS RAINFALL FOR WATERSHED =   .64


LONGEST FLOWPATH =  7565.36 METERS    SLOPE =   .0182
LENGTH OF MAINSTREAM =  6588.67 METERS    SLOPE =  .0140
TIME OF CONCENTRATION =   756.18 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
         42          445          322          547          561          860
        446          465          498          734          699          440
        426          352          279          393          369          324
        508          644          448           97           68           39
         43           60          115           41           54           62
         73           46           43           57           52           74
         64           92           56           55           66           70
         65           37           35           87          102          100
         36           58           75           41           64           62
         65           87           84          112           70           46
         28           25           24           17           20           24
         28           19           21           17           14            8
         15           13            9            6
```

Figure C-7 Data file for sub watershed 2 of Thompson Run

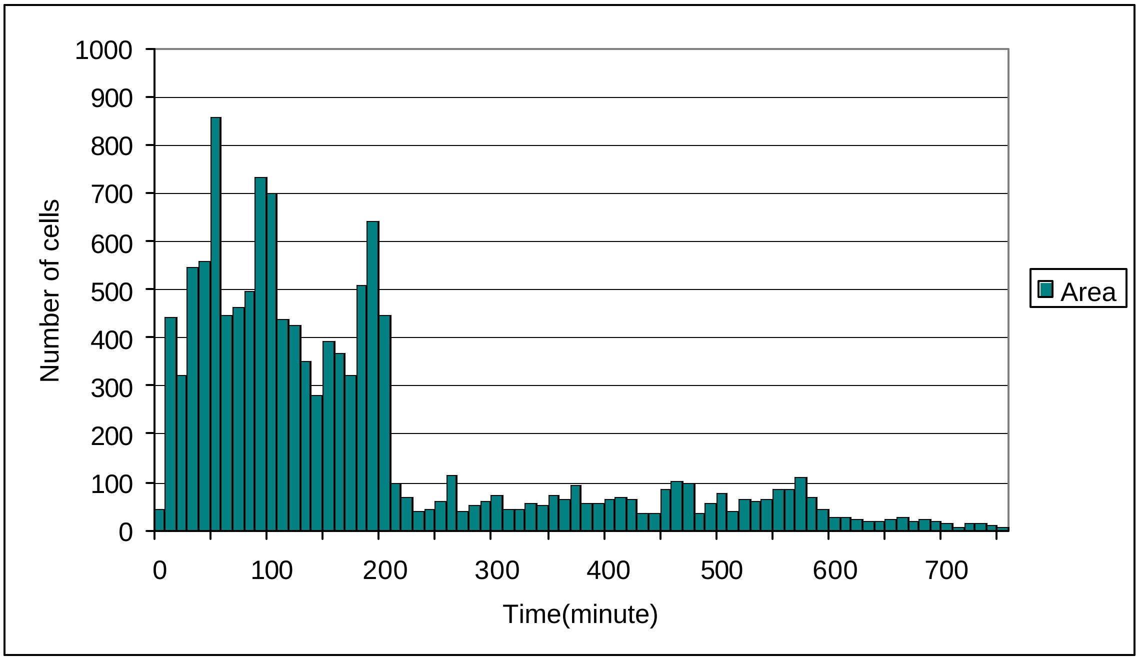

Figure C-8 Time area histogram for sub watershed 2 of Thompson Run

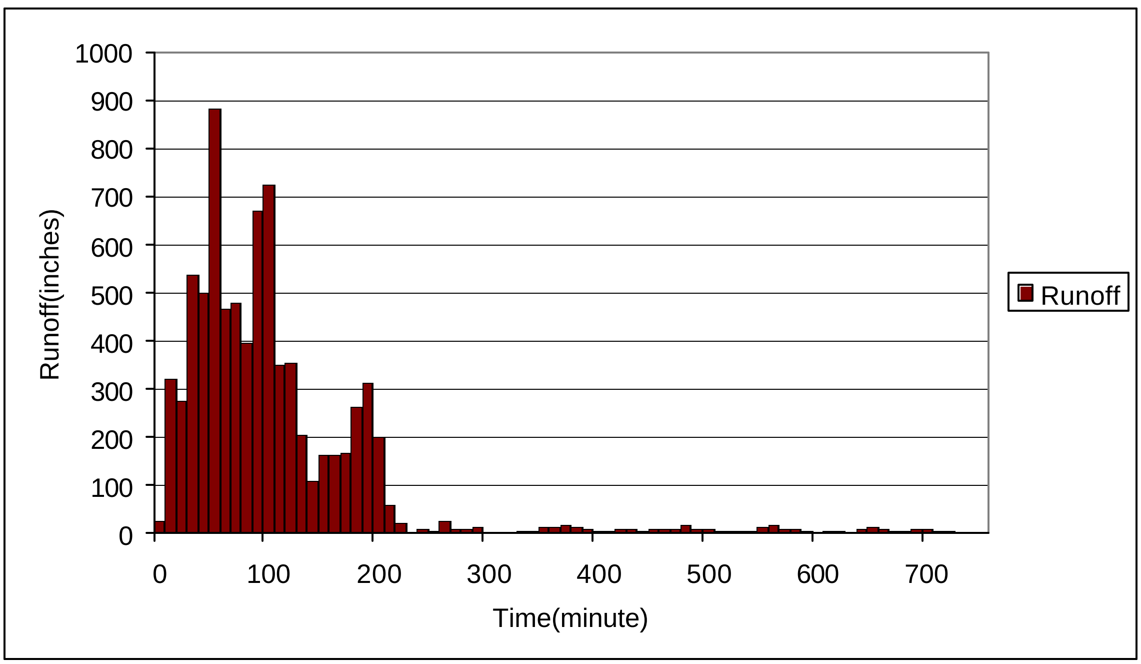

Figure C-9 Runoff time histogram for sub watershed 2 of Thompson Run

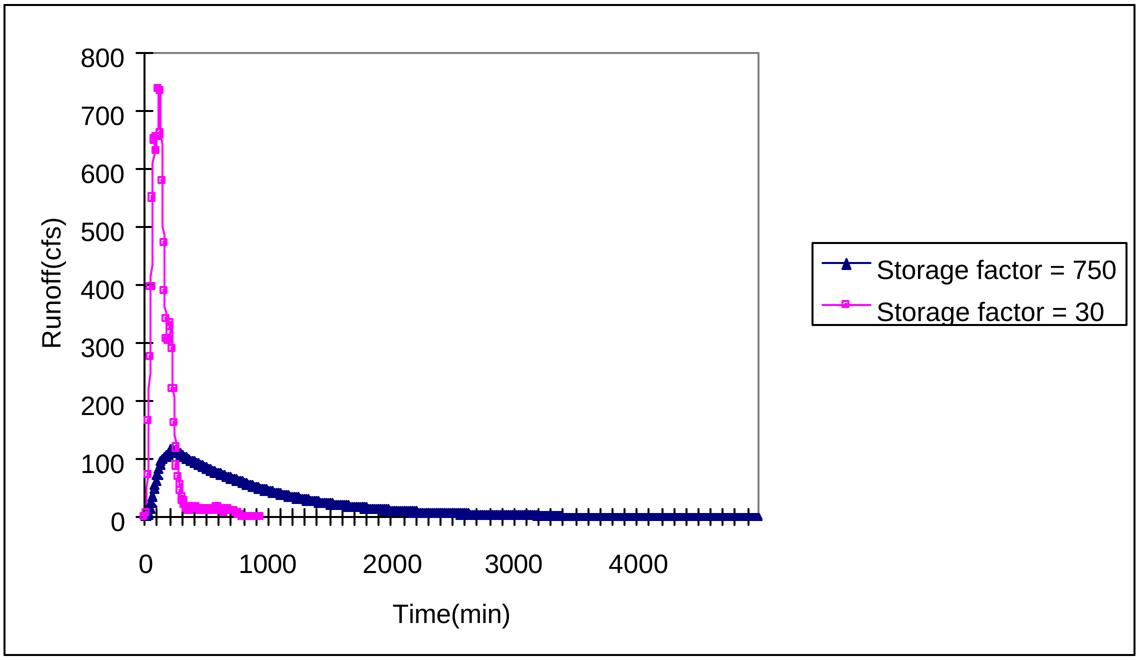

Figure C-10 Direct Runoff Hydrograph for sub watershed 2 of Thompson Run

Results for sub watershed 3 of Thompson Run watershed

```
THE CURVE-NUMBER CALCULATION FILE
---------------------------------


WATERSHED NUMBER:  3


NUMBER OF CELLS IN THE WATERSHED:      5281



CURVE NUMBER                    NUMBER OF CELLS
------------                    ---------------
     45                               409
     55                               447
     68                                42
     85                               658
     86                              1113
     89                                98
     90                               597
     92                              1898
     94                                19


CURVE NUMBER FOR THE WATERSHED: 83
```

Figure C-11 Curve Number file for sub watershed 3 of Thompson Run

```
WATERSHED NUMBER  3


NUMBER OF CELLS =   5280


CURVE NUMBER = 83


AVERAGE EXCESS RAINFALL FOR WATERSHED =   .89


LONGEST FLOWPATH =  4469.48 METERS    SLOPE =   .0208
LENGTH OF MAINSTREAM =  3612.79 METERS    SLOPE =  .0144
TIME OF CONCENTRATION =   483.22 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
          50          164          230          500          471          449
         588         1013          308          509          127           96
         107           57           26           23           25           76
          82           63           18            7            5            2
           5           10           16            9            5            2
          11           12            8           17           22            9
          17           20           18            8            3            3
           0            4            7           17           29           27
           4
```

Figure C-12 Data file for sub watershed 3 of Thompson Run

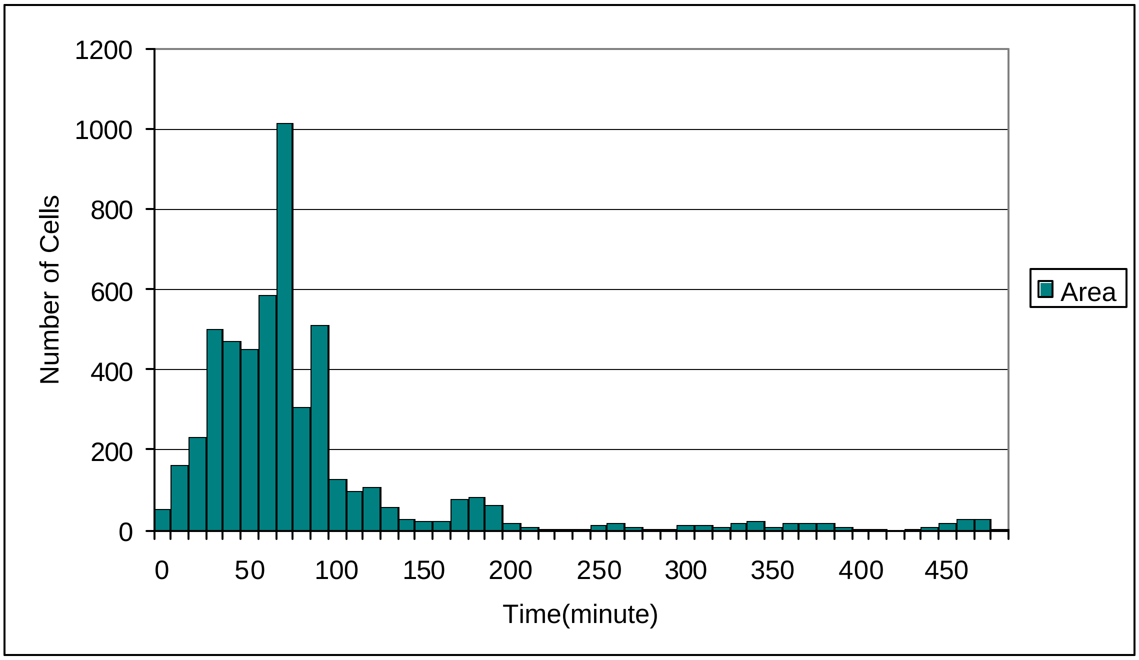

Figure C-13 Time area histogram for sub watershed 3 of Thompson Run

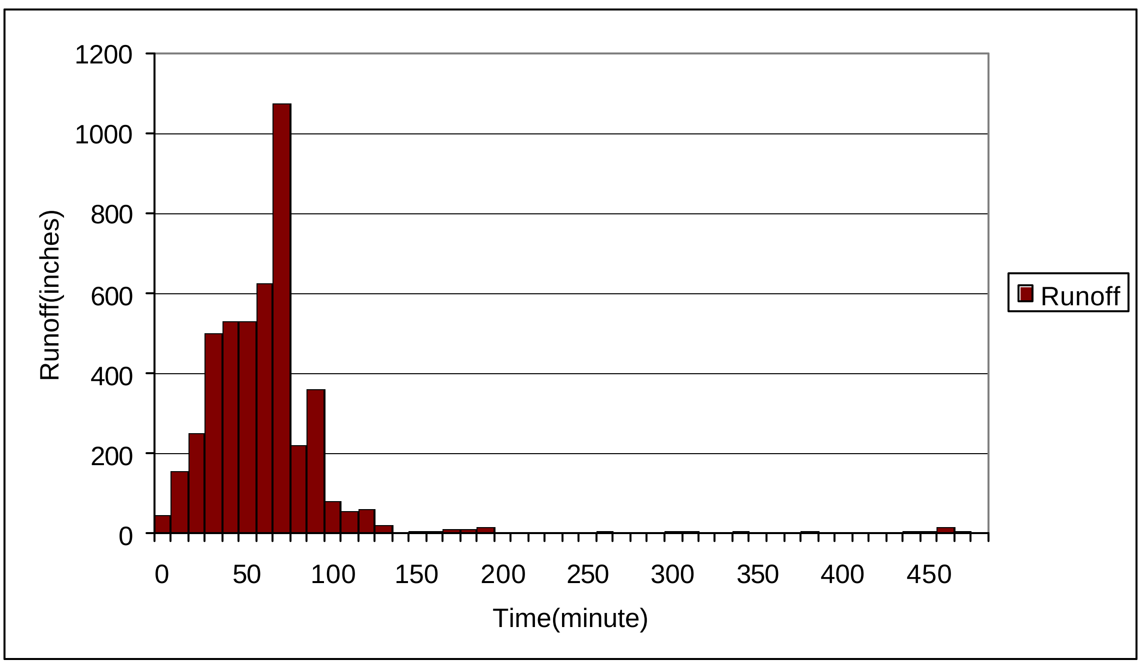

Figure C-14 Runoff time histogram for sub watershed 3 of Thompson Run

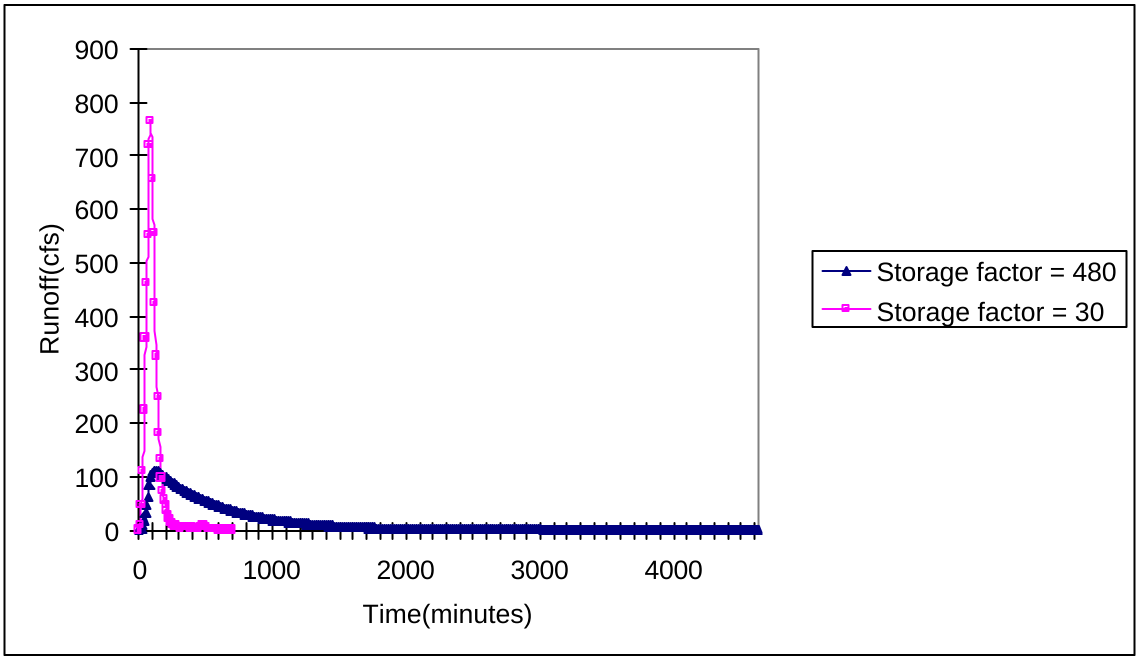

Figure C-15 Direct Runoff Hydrograph for sub watershed 3 of Thompson Run

Results for sub watershed 4 for Thompson Run watershed

```
THE CURVE-NUMBER CALCULATION FILE
---------------------------------

WATERSHED NUMBER:  4

NUMBER OF CELLS IN THE WATERSHED:      7516

CURVE NUMBER                    NUMBER OF CELLS
------------                    ---------------
     45                              1968
     55                               309
     66                               274
     68                                10
     85                                 8
     86                              1291
     89                               216
     90                              1141
     92                              1292
     94                              1007

      CURVE NUMBER FOR THE WATERSHED: 77
```

Figure C-16 Curve Number file for sub watershed 4 of Thompson Run

```
WATERSHED NUMBER  4

NUMBER OF CELLS =   7515

CURVE NUMBER = 77

AVERAGE EXCESS RAINFALL FOR WATERSHED =   .87

LONGEST FLOWPATH =  6147.72 METERS    SLOPE =   .0211
LENGTH OF MAINSTREAM =  5253.75 METERS    SLOPE =  .0118
TIME OF CONCENTRATION =   717.28 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
          17          85          86          69         115         268
         226         193         399         733         479         414
         217         143         302         398         508         338
         134          43          24          26          40          82
          54          90          60          34          41          38
          40          52          55          70          81          93
          73          65          27          44          54          54
          81          71          30          30          21          29
          30          37          29          40          40          40
          39          30          38          50          44          40
          40          44          52          45          44          40
          40          36          40          26          18           6
```

Figure C-17 Data file for sub watershed 4 of Thompson Run

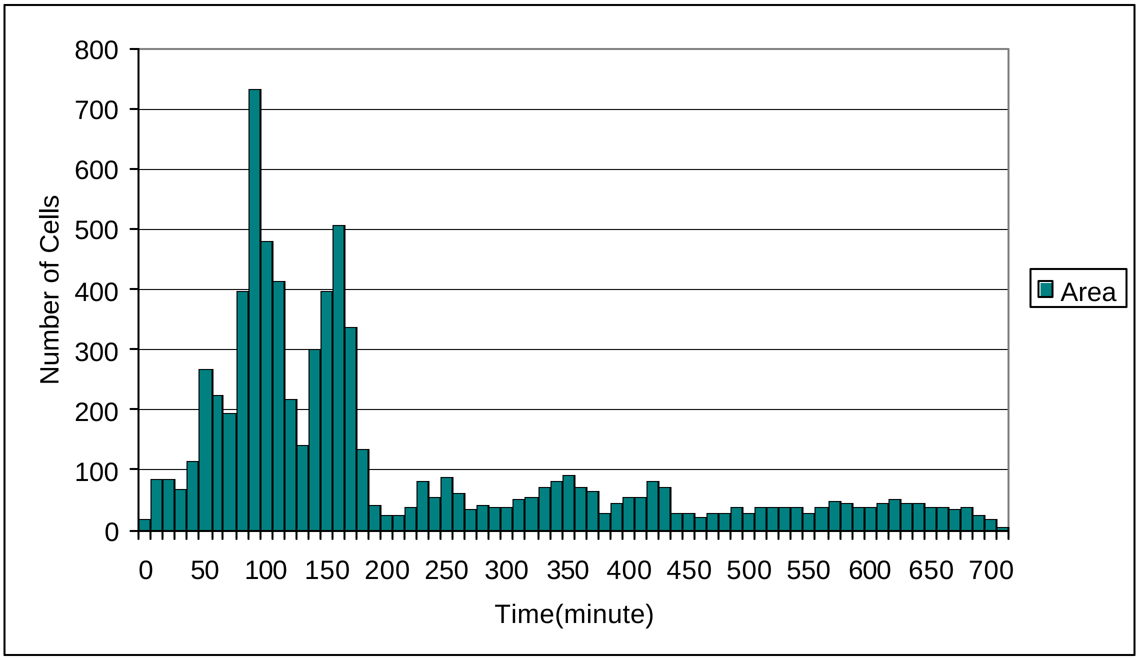

Figure C-18 Time area histogram for sub watershed 4 of Thompson Run

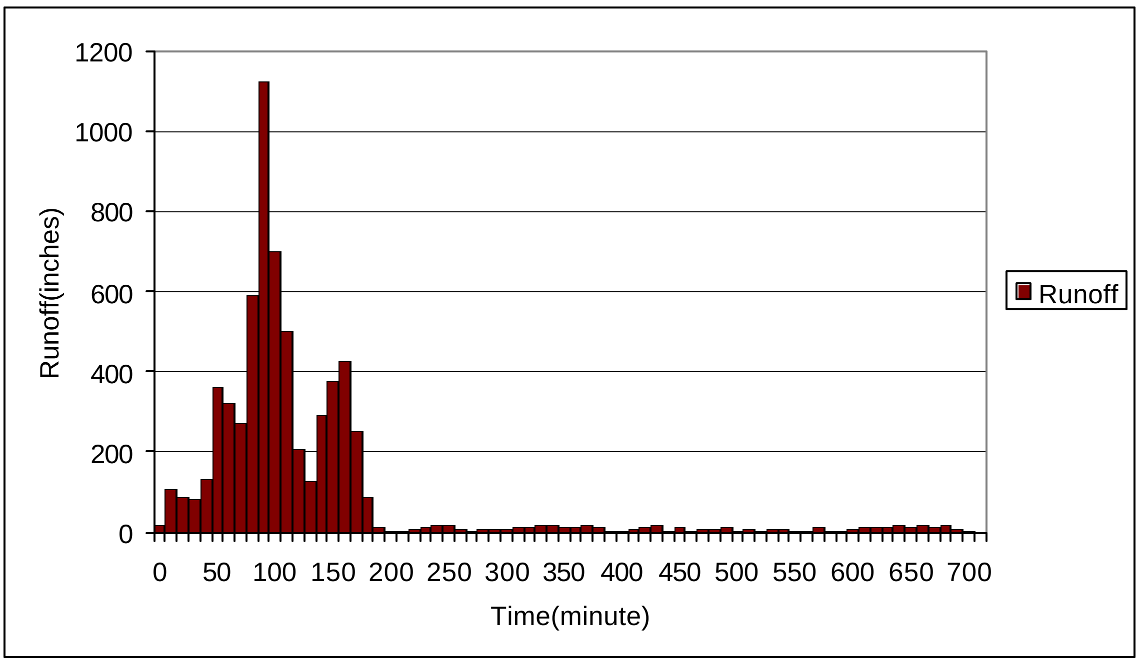

Figure C-19 Runoff time histogram for sub watershed 4 of Thompson Run

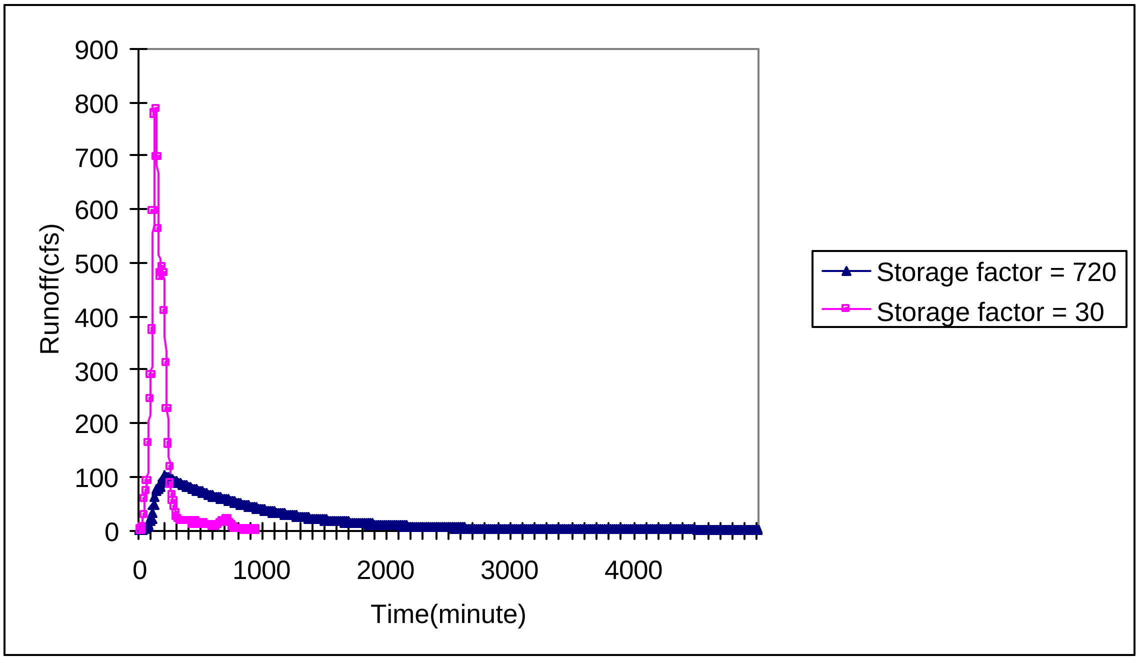

Figure C-20 Direct Runoff Hydrograph for sub watershed 4 of Thompson Run

Results for sub watershed 5 of Thompson Run watershed

```
                THE CURVE-NUMBER CALCULATION FILE
                ---------------------------------


WATERSHED NUMBER:  5


NUMBER OF CELLS IN THE WATERSHED:      9483



CURVE NUMBER                        NUMBER OF CELLS
------------                        ---------------
     45                                  848
     55                                  637
     66                                 1001
     68                                 1134
     86                                 2215
     89                                  714
     90                                  779
     92                                 1793
     94                                  362


     CURVE NUMBER FOR THE WATERSHED: 78
```

Figure C-21 Curve Number file for sub watershed 5 of Thompson Run

WATERSHED NUMBER 5

NUMBER OF CELLS =   9482

CURVE NUMBER = 78

AVERAGE EXCESS RAINFALL FOR WATERSHED =   .96

LONGEST FLOWPATH = 5762.87 METERS   SLOPE =   .0179
LENGTH OF MAINSTREAM = 4811.03 METERS   SLOPE = .0104
TIME OF CONCENTRATION =   625.34 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN

7	97	160	119	218	307
315	460	399	321	435	350
514	598	429	458	383	284
193	104	87	99	149	133
155	263	173	124	152	163
160	240	236	173	114	93
42	74	53	41	55	58
50	28	60	58	48	27
28	41	43	21	14	16
9	15	11	6	5	3
5	4	1			

Figure C-22 Data file for sub watershed 5 of Thompson Run

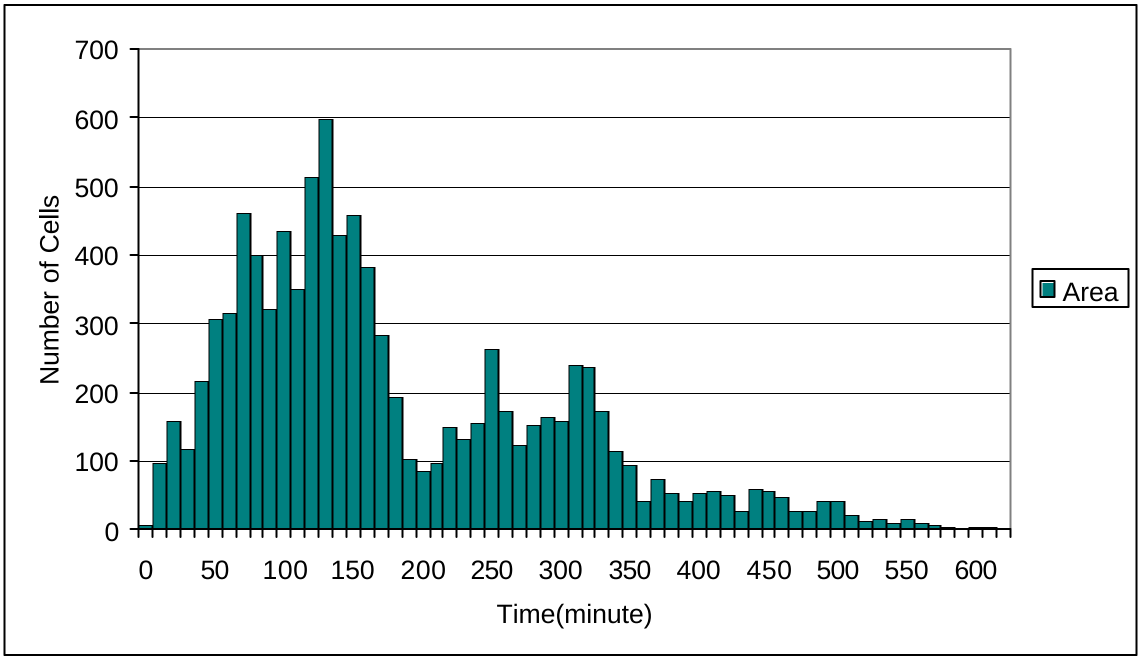

Figure C-23 Time area histogram for sub watershed 5 of Thompson Run

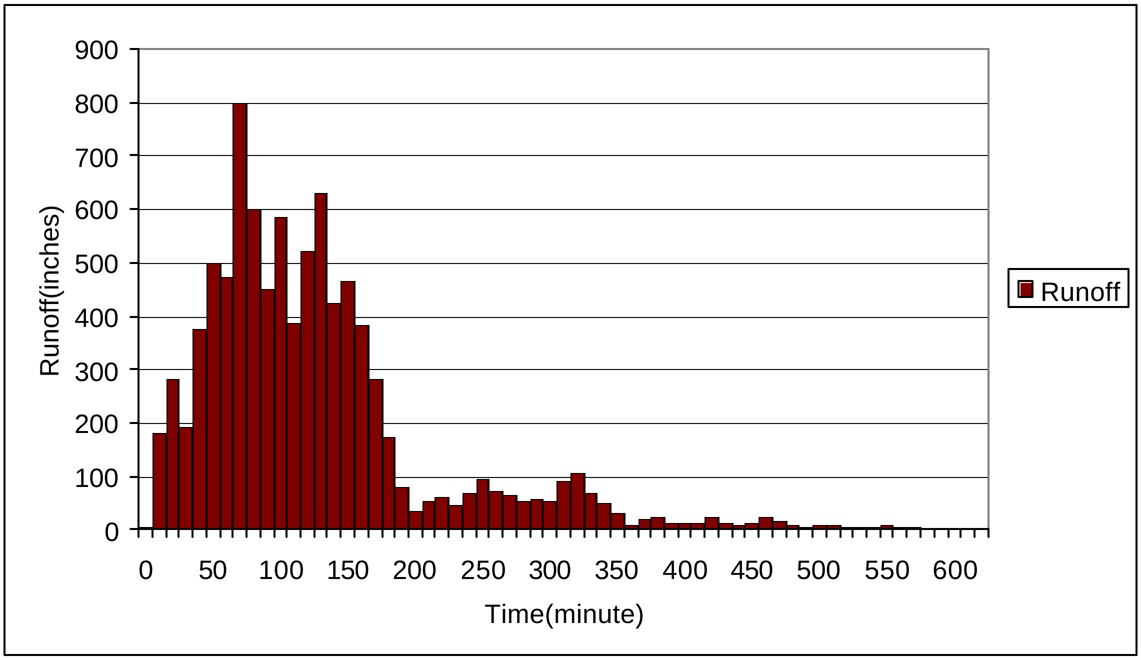

Figure C-24 Runoff time histogram for sub watershed 5 of Thompson Run

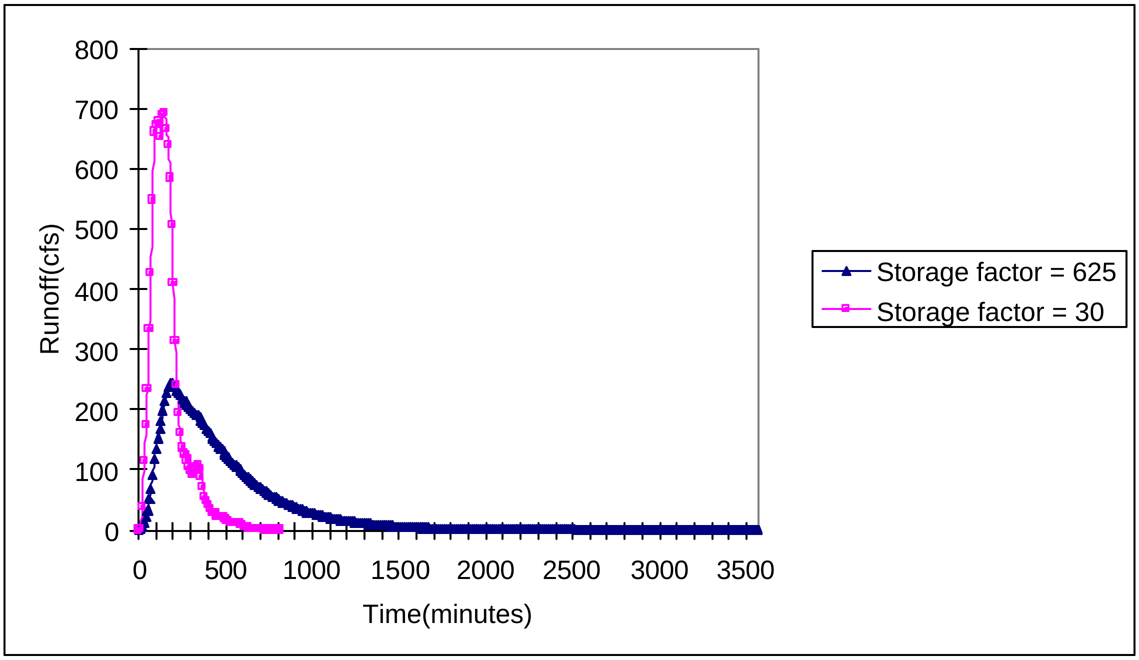

Figure C-25 Direct Runoff Hydrograph for sub watershed 5 of Thompson Run

Results for sub watershed 1 of Nine Mile Run watershed

```
THE CURVE-NUMBER CALCULATION FILE
---------------------------------


WATERSHED NUMBER:  1


NUMBER OF CELLS IN THE WATERSHED:      3124



CURVE NUMBER                    NUMBER OF CELLS
------------                    ---------------
     55                               586
     70                                 6
     77                                88
     81                               439
     85                               281
     89                              1244
     92                               469
     95                                11


       CURVE NUMBER FOR THE WATERSHED: 82
```

Figure C-26 Curve Number file for sub watershed 1 of Nine Mile Run

```
WATERSHED NUMBER  1


NUMBER OF CELLS =   3123


CURVE NUMBER = 82


AVERAGE EXCESS RAINFALL FOR WATERSHED =   .35


LONGEST FLOWPATH =  3732.79 METERS    SLOPE =   .0182
LENGTH OF MAINSTREAM =  3287.94 METERS    SLOPE =  .0192
TIME OF CONCENTRATION =   338.38 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
          1          398          477          346          228          269
        244          109           97           85           76           53
         56           68           59           17           14           46
        100           80           39           18           24           22
         22           25           17           11            6            8
         24           52           19           12
```

Figure C-27 Data file for sub watershed 1 of Nine Mile Run

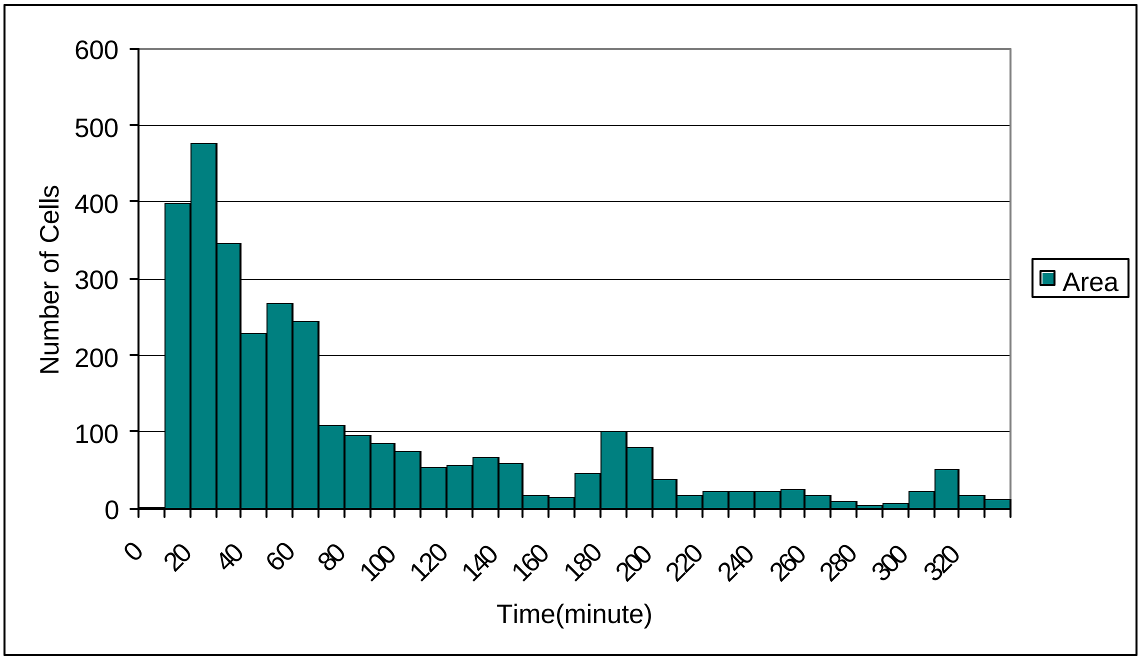

Figure C-28 Time area histogram for sub watershed 1 of Nine Mile Run

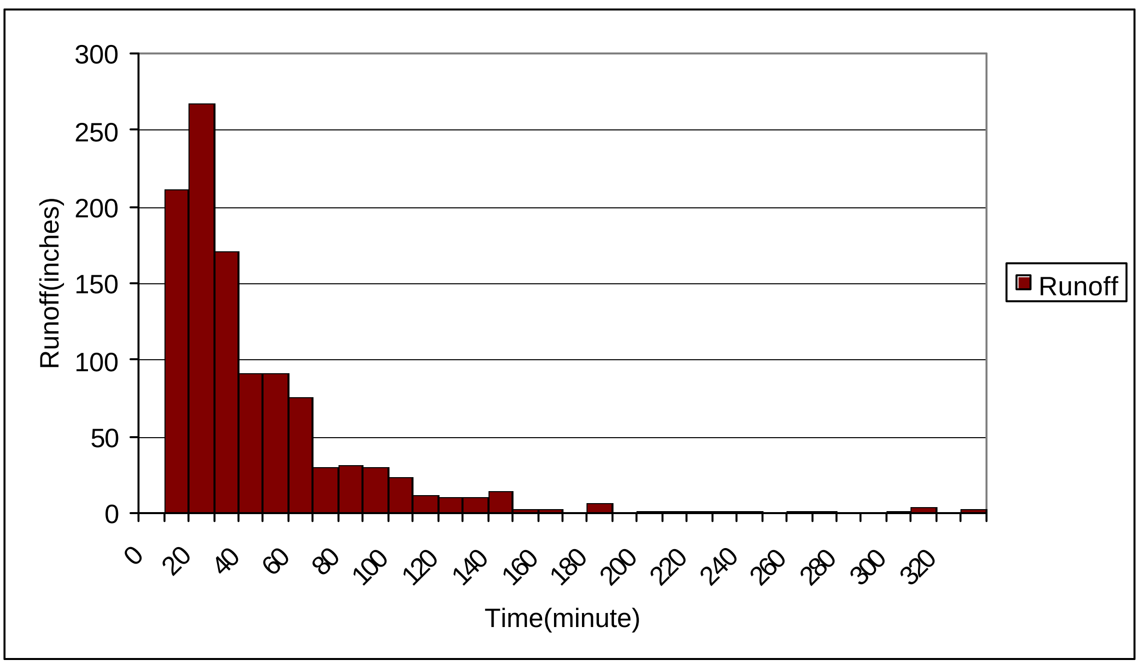

Figure C- 29 Runoff time histogram for sub watershed 1 of Nine Mile Run

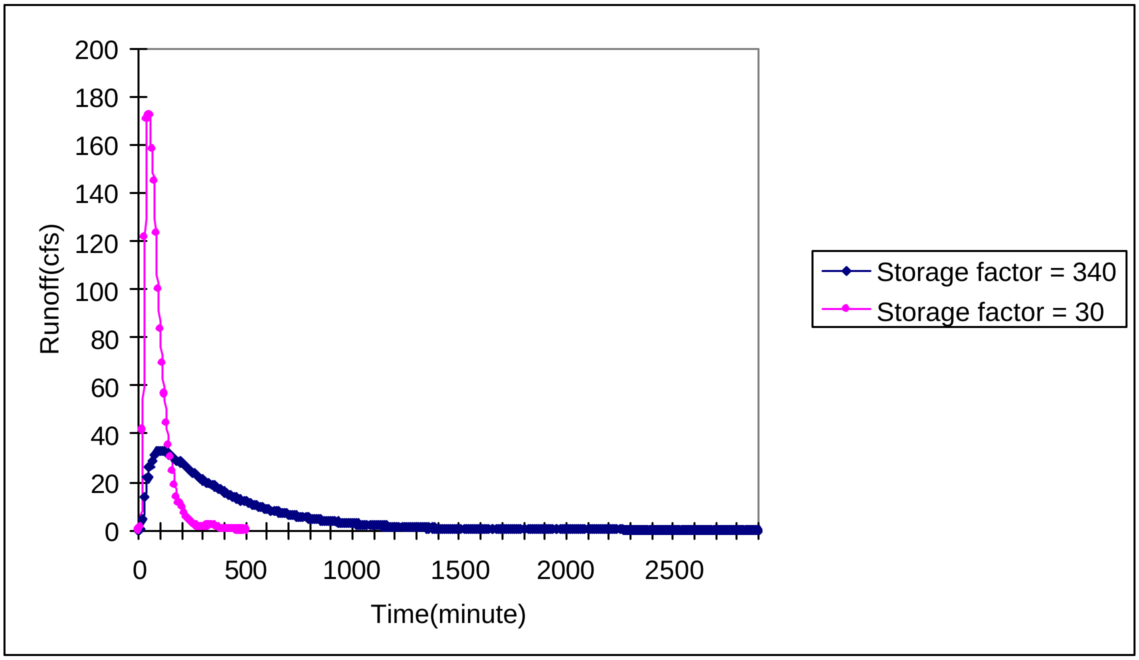

Figure C-30 Direct Runoff Hydrograph for sub watershed 1 of Nine Mile Run

Results for sub watershed 2 of Nine Mile Run watershed

```
THE CURVE-NUMBER CALCULATION FILE
---------------------------------


WATERSHED NUMBER:  2


NUMBER OF CELLS IN THE WATERSHED:      3824



CURVE NUMBER                    NUMBER OF CELLS
------------                    ---------------
     55                               44
     70                              442
     77                              109
     81                              261
     85                              711
     88                              577
     89                              613
     92                              540
     95                              527


      CURVE NUMBER FOR THE WATERSHED: 86
```

Figure C-31 Curve Number file for sub watershed 2 of Nine Mile Run

```
WATERSHED NUMBER  2


NUMBER OF CELLS =   3823


CURVE NUMBER = 86


AVERAGE EXCESS RAINFALL FOR WATERSHED =   .65


LONGEST FLOWPATH =  4519.19 METERS    SLOPE =   .0217
LENGTH OF MAINSTREAM =  3977.06 METERS    SLOPE =  .0199
TIME OF CONCENTRATION =   207.40 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
         11          204          428          417          564          275
        569          264          109          173          234          225
        135           73           67           18            1            0
          0           28           27
```

Figure C-32 Data file for sub watershed 2 of Nine Mile Run

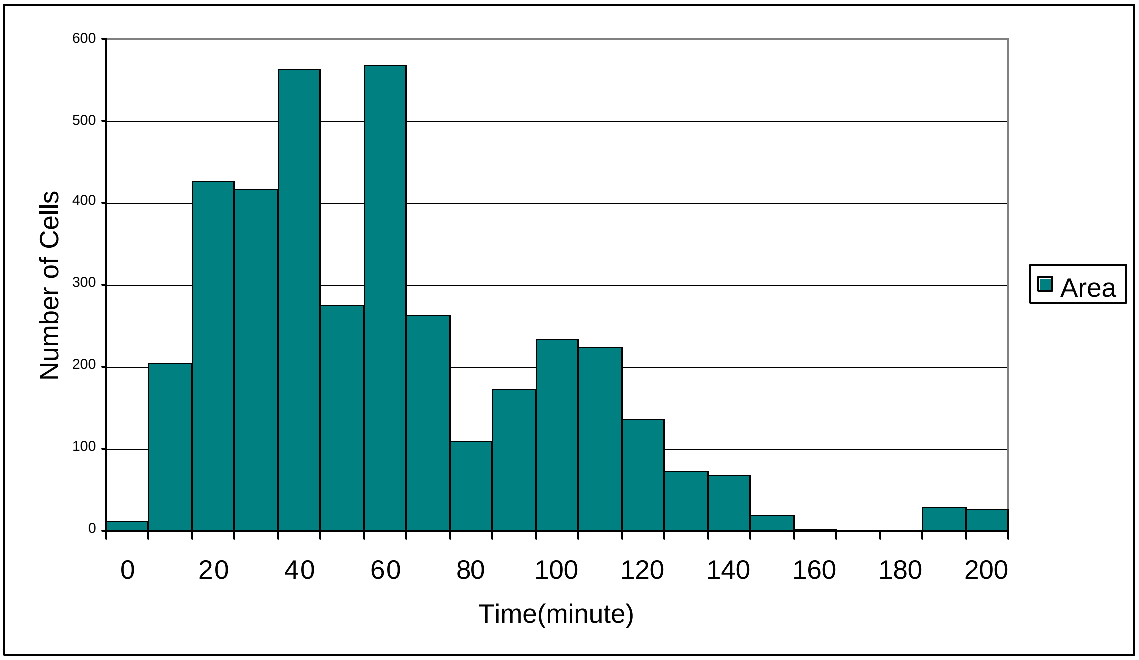

Figure C-33 Time area histogram for sub watershed 2 of Nine Mile Run

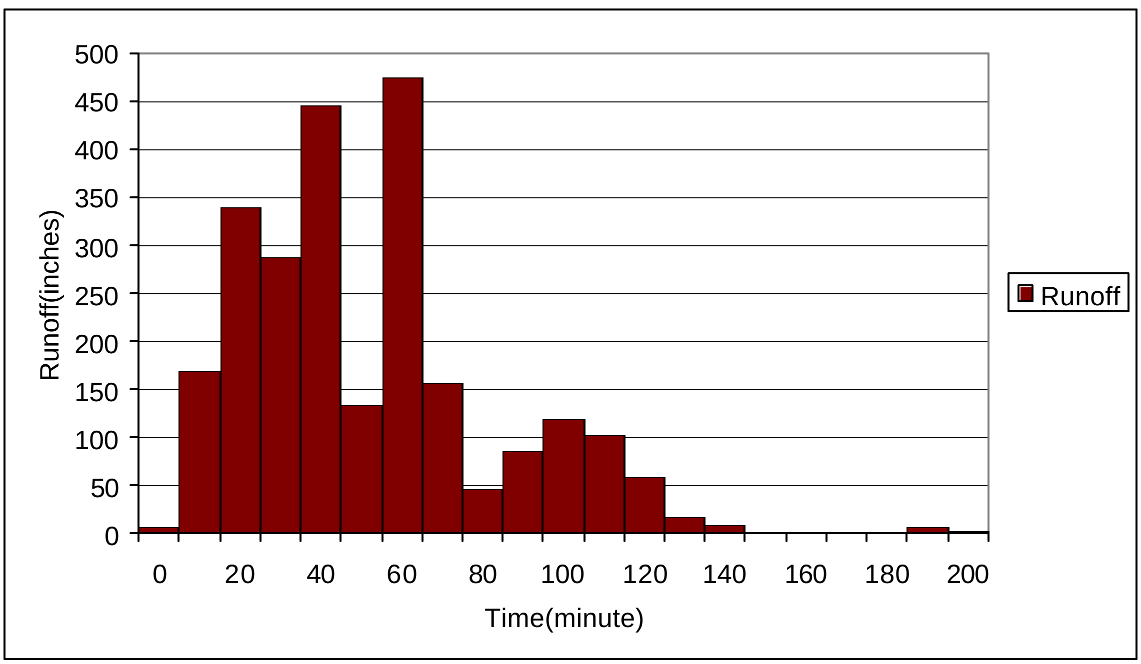

Figure C-34 Runoff time histogram for sub watershed 2 of Nine Mile Run

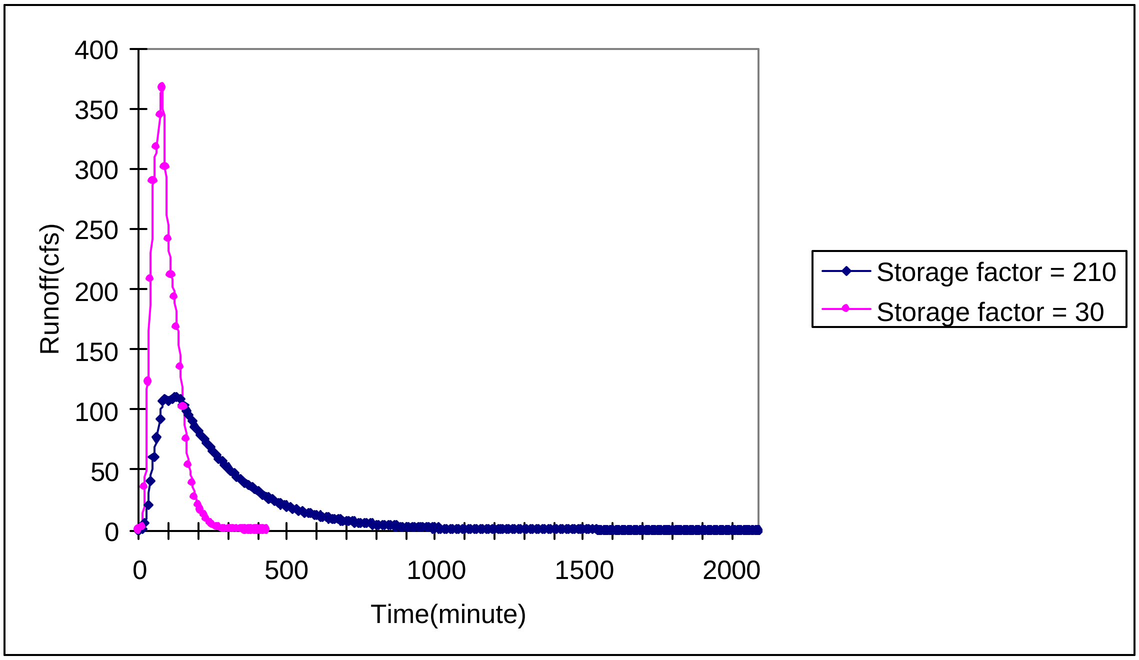

Figure C-35 Direct Runoff Hydrograph for sub watershed 2 of Nine Mile Run

Results for sub watershed 3 of Nine Mile Run watershed

THE CURVE-NUMBER CALCULATION FILE

WATERSHED NUMBER: 3

NUMBER OF CELLS IN THE WATERSHED: 3754

CURVE NUMBER	NUMBER OF CELLS
55	663
70	124
77	909
81	256
85	956
89	290
92	401
95	155

CURVE NUMBER FOR THE WATERSHED: 79

Figure C-36 Curve Number file for sub watershed 3 of Nine Mile Run

```
WATERSHED NUMBER  3


NUMBER OF CELLS =   3753


CURVE NUMBER = 79


AVERAGE EXCESS RAINFALL FOR WATERSHED =   .59


LONGEST FLOWPATH =  2857.65 METERS    SLOPE =   .0434
LENGTH OF MAINSTREAM =  2543.09 METERS    SLOPE =  .0315
TIME OF CONCENTRATION =   229.77 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
          69          180          472          374          260          392
         442          544          441          253           68           66
          12            4           14           17           45           58
          23            6            4            4            4
```

Figure C-37 Data file for sub watershed 3 of Nine Mile Run

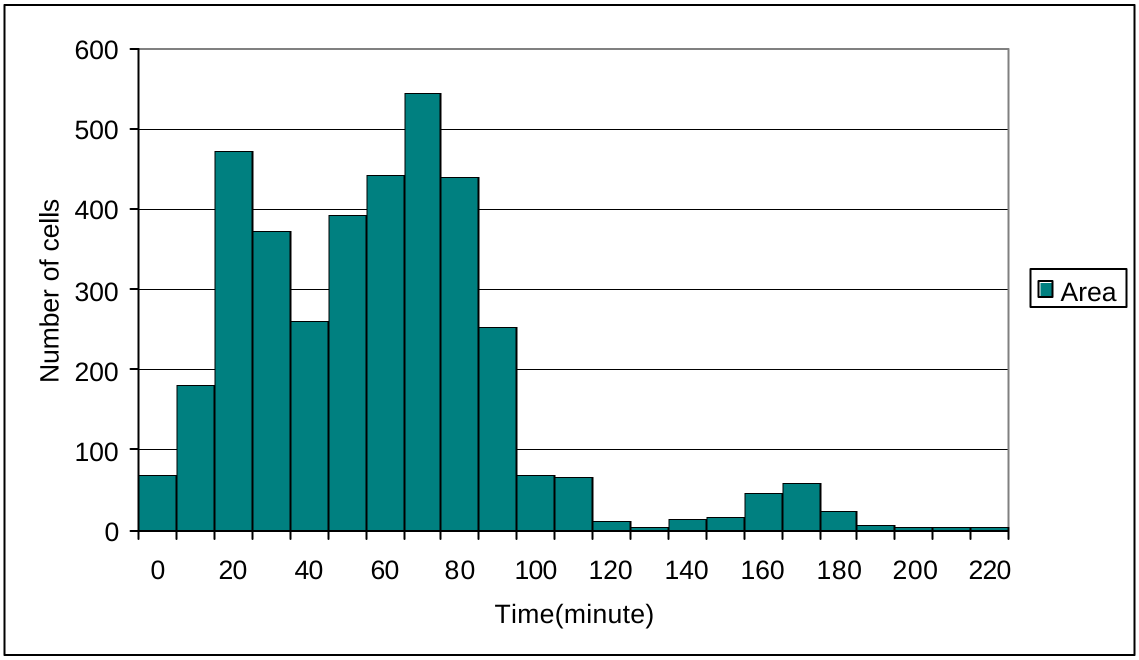

Figure C-38 Time area histogram for sub watershed 3 of Nine Mile Run

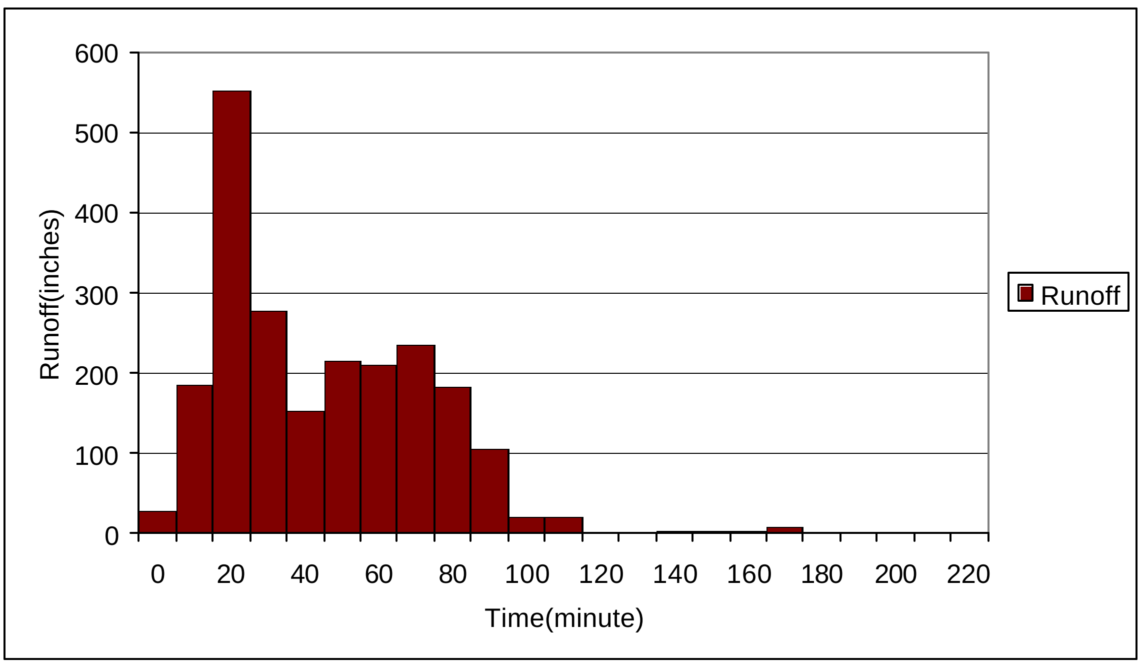

Figure C-39 Runoff time histogram for sub watershed 3 of Nine Mile Run

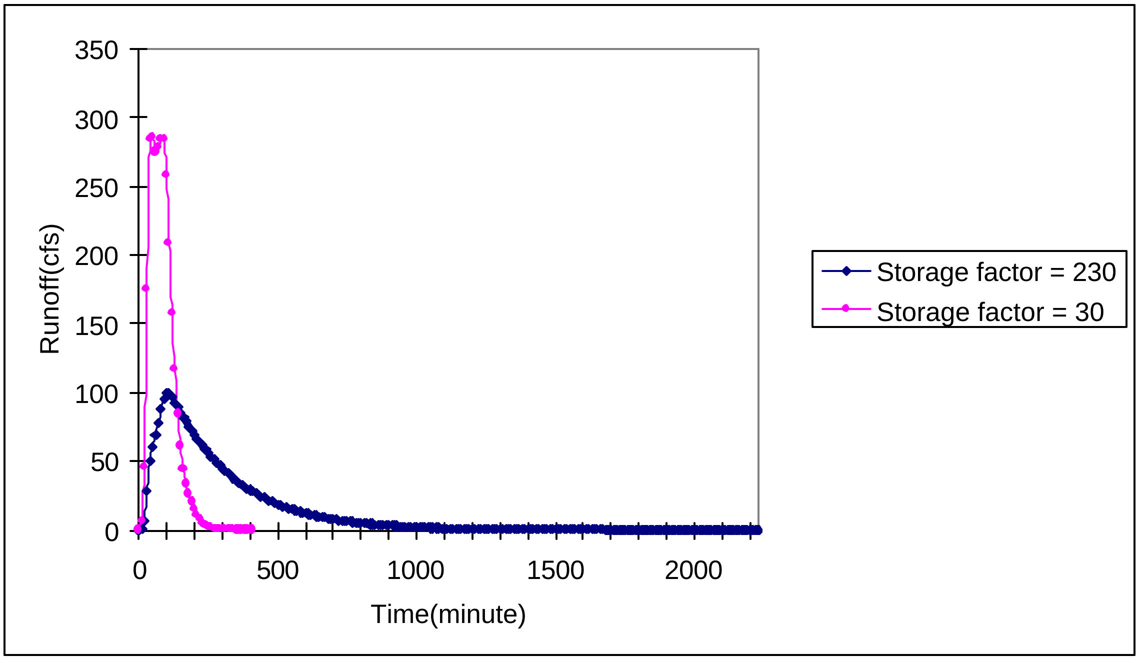

Figure C-40 Direct Runoff Hydrograph for sub watershed 3 of Nine Mile Run

Results for sub watershed 4 for Nine Mile Run watershed

```
        THE CURVE-NUMBER CALCULATION FILE
        ---------------------------------


WATERSHED NUMBER:  4


NUMBER OF CELLS IN THE WATERSHED:      4644



CURVE NUMBER                        NUMBER OF CELLS
------------                        ---------------
     55                                   9
     70                                  24
     77                                 713
     81                                 401
     85                                1200
     88                                 344
     89                                 270
     92                                1484
     95                                 199


CURVE NUMBER FOR THE WATERSHED: 87
```

Figure C-41 Curve Number file for sub watershed 4 of Nine Mile Run

```
WATERSHED NUMBER  4


NUMBER OF CELLS =   4643


CURVE NUMBER = 87


AVERAGE EXCESS RAINFALL FOR WATERSHED =  1.13


LONGEST FLOWPATH =  3589.19 METERS    SLOPE =   .0318
LENGTH OF MAINSTREAM =  3189.78 METERS    SLOPE =  .0223
TIME OF CONCENTRATION =   169.22 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
          32          158          335          655          963         1103
         450          319          398          143           57           19
           1            0            2            4            3
```

Figure C-42 Data file for sub watershed 4 of Nine Mile Run

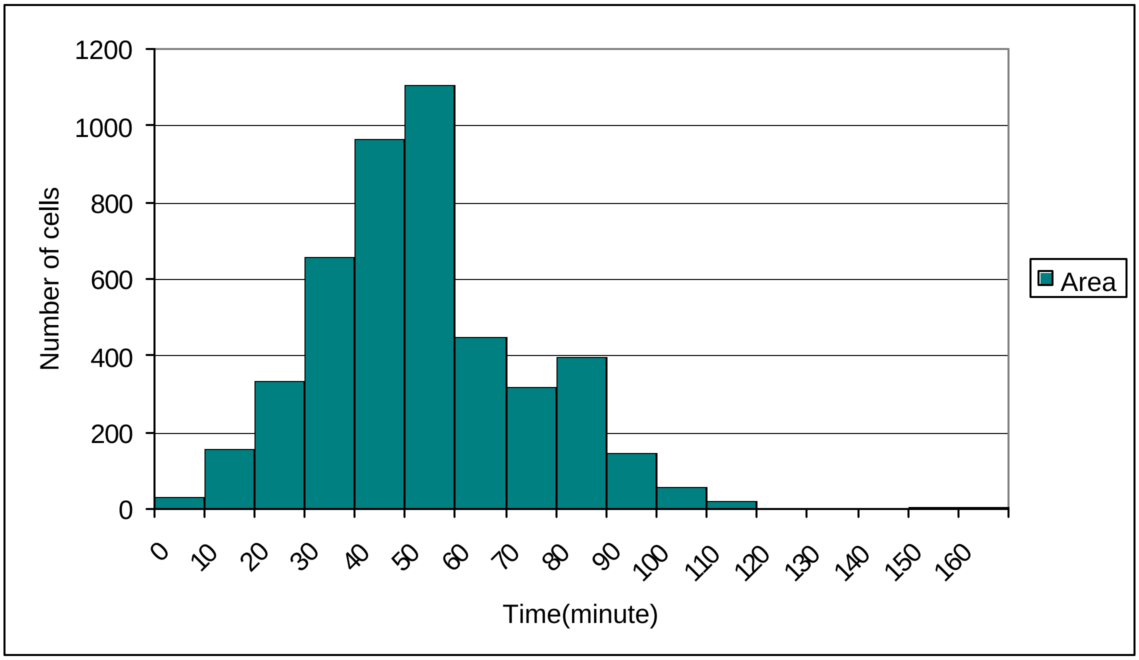

Figure C-43 Time area histogram for sub watershed 4 of Nine Mile Run

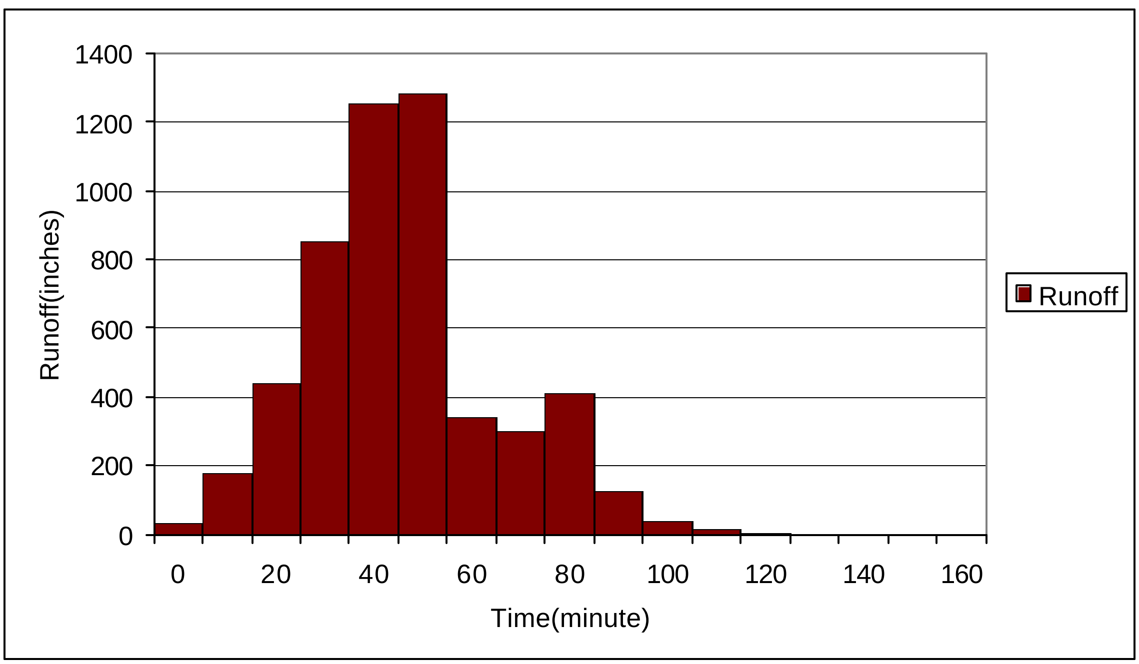

Figure C-44 Runoff time histogram for sub watershed 4 of Nine Mile Run

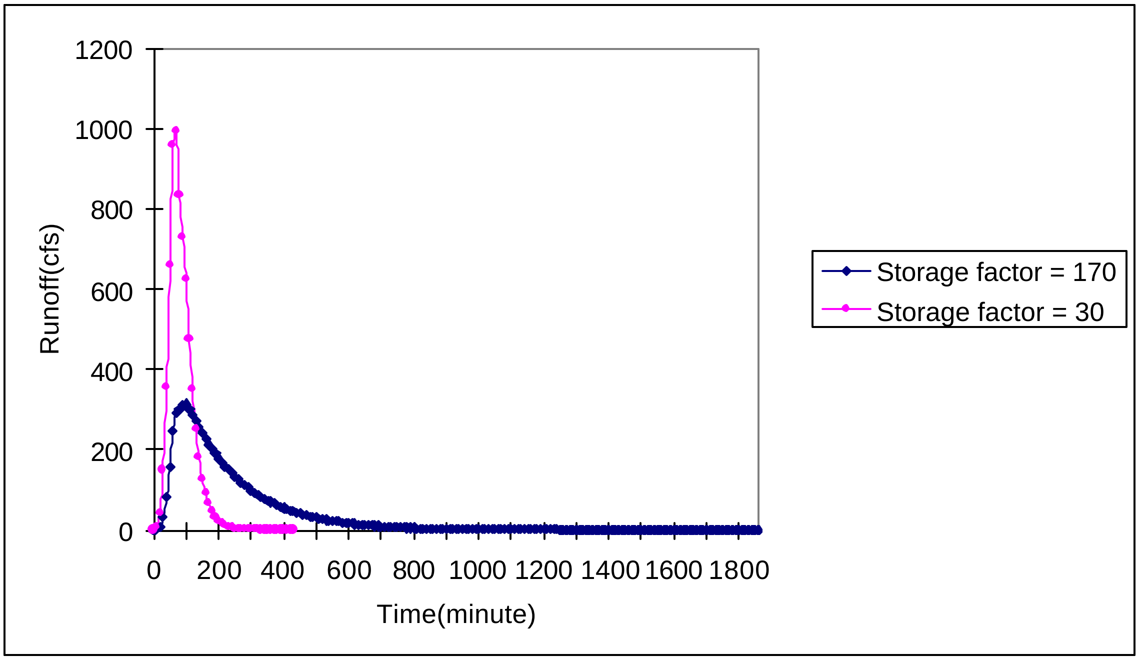

Figure C-45 Direct Runoff Hydrograph for sub watershed 4 for Nine Mile Run

Results for sub watershed 5 of Nine Mile Run watershed

```
        THE CURVE-NUMBER CALCULATION FILE
        ---------------------------------


WATERSHED NUMBER:  4


NUMBER OF CELLS IN THE WATERSHED:      4644



CURVE NUMBER                        NUMBER OF CELLS
------------                        ---------------
     55                                   9
     70                                  24
     77                                 713
     81                                 401
     85                                1200
     88                                 344
     89                                 270
     92                                1484
     95                                 199


      CURVE NUMBER FOR THE WATERSHED: 87
```

Figure C-46 Curve Number file for sub watershed 5 of Nine Mile Run

```
WATERSHED NUMBER  4


NUMBER OF CELLS =   4643


CURVE NUMBER = 87


AVERAGE EXCESS RAINFALL FOR WATERSHED =  1.13


LONGEST FLOWPATH =  3589.19 METERS    SLOPE =   .0318
LENGTH OF MAINSTREAM =  3189.78 METERS    SLOPE =  .0223
TIME OF CONCENTRATION =   169.22 MINUTES
TIME INTERVAL = 10 MINUTES

NO. OF CELLS PER TIME INTERVAL, STARTING AT 10 MIN
          32          158          335          655          963         1103
         450          319          398          143           57           19
           1            0            2            4            3
```

Figure C-47 Data file for sub watershed 5 of Nine Mile Run

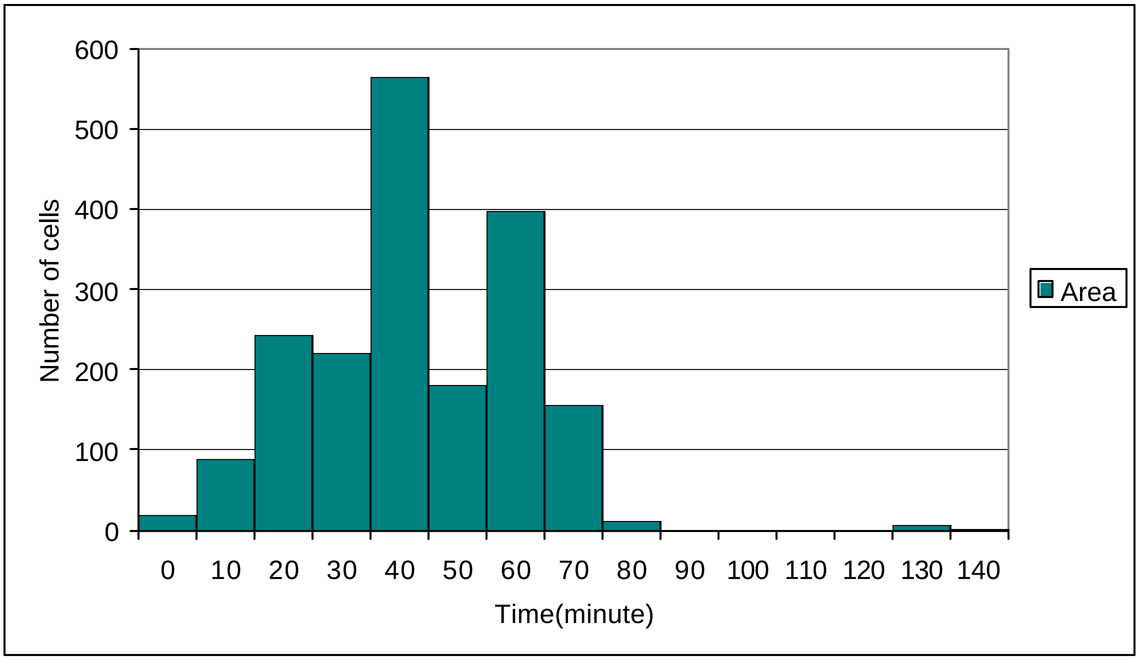

Figure C-48 Time area histogram for sub watershed 5 of Nine Mile Run

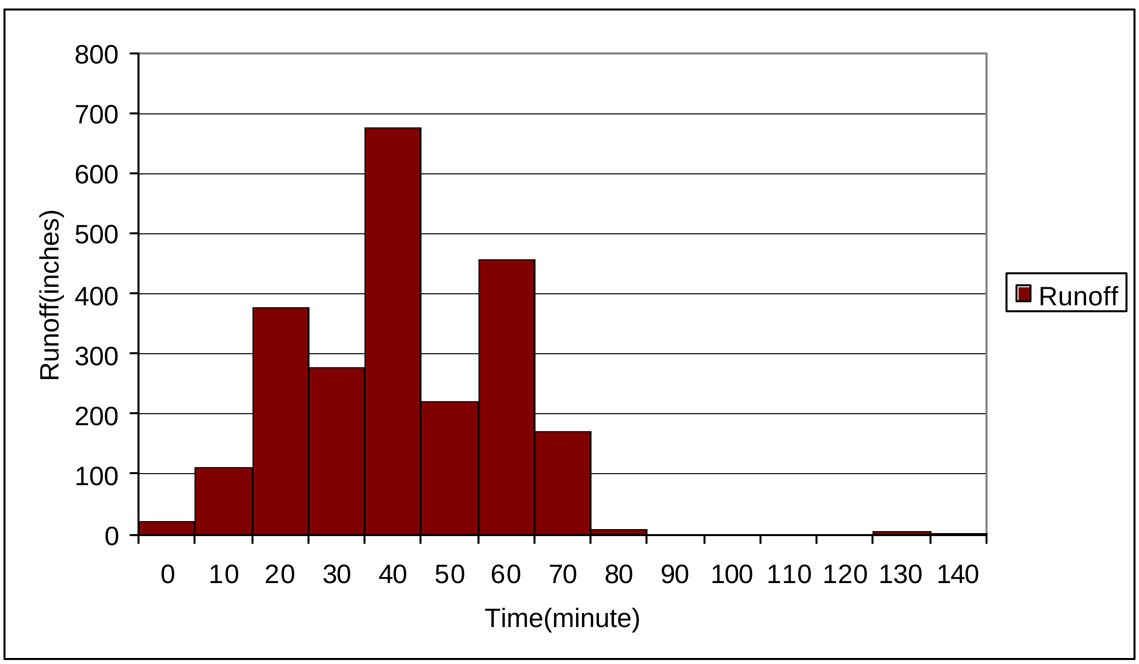

Figure C-49 runoff time histogram for sub watershed 5 of Nine Mile Run

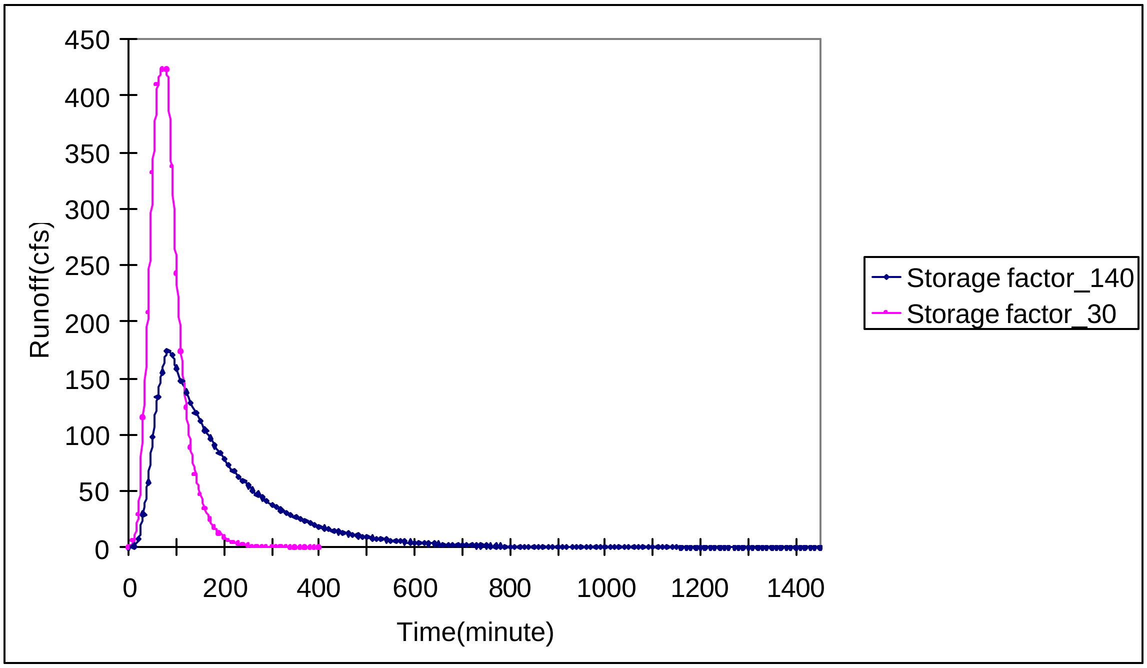

Figure C-50 Direct runoff histogram for sub watershed 5 of Nine Mile Run

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Ajward, M. H., "A Spatially Distributed Unit Hydrograph model using a Geographic Information Systems"(Ph. D. dissertation, University of Calgary, Calgary, 1996).

2. Muzik, I. and Chang, C., "A Microcomputer based GIS for Hydrologic Modeling", Microcomputers in Civil Engineering, 8, 1993, pp. 355-365.

3. Sherman, L. K., "Stream Flow from Rainfall by the Unit-graph method", Eng. News Record, Vol. 108, 1932, pp. 501-505.

4. Maidment, D. R., Olivera, F., "Storm Runoff Computation using Spatially Distributed Terrain parameters", 1998.

5. Haan, C. T., Barfield, B. J. and Hayes, J. C., Design Hydrology and Sedimentology for Small Catchments (Academic Press, Inc., 1994), pp. 38.

6. Chow, V.T., Maidment, D. R. and Mays, L. W., Applied Hydrology (McGraw Hill Inc., New York, 1988), pp.7.

7. Asante, K. O., "Approaches to Continental Scale River Flow Routing" (Ph. D. dissertation, University of Texas at Austin, 2000).

8. Peters, John, Evans, Tom and Brunner, Gary, " GIS Data Exchange for Hydraulic and Hydrologic Models", Proceedings from the First Federal Interagency Hydrologic Modeling Conference, Nevada, (Nevada: Subcommittee On Hydrology (SOH), Interagency Advisory Committee on Water Data), April 19-23, 1998.

9. Olivera, F., Famiglietti, J. S. and Asante, K. O., "Global Scale Flow Routing Using a Source to Sink Algorithm", 2000.

10. Clark, C.O., "Storage and the Unit Hydrograph", Transactions ASCE, Vol 110, 1945, pp. 1419-1446.

11. Chow, V.T., Maidment, D. R. and Mays, L. W., Applied Hydrology (McGraw Hill Inc., New York, 1988), pp.31.

12. Chow, V.T., Maidment, D. R. and Mays, L. W., Applied Hydrology (McGraw Hill Inc., New York, 1988), pp.281.

13. Todini, E., "Rainfall-runoff Modeling – Past, Present and Future", Journal of Hydrology, Vol 100, 1988, pp. 341-352.

14. Synder, F. F., "Synthetic Unit Graph", Transactions American Geophysics Union, Vol 19, 1938, pp. 447-454.

15. Almedeij, J. H., "Automatic Generation of Runoff Curve Numbers with GIS" (unpublished M.S. thesis, School of Engineering, University of Pittsburgh, 1998).

16. Maidment, D. R., Grid based Computation of Runoff: A preliminary assessment, (Hydrologic Engineering Center, US Army Corps of Engineers, Davis, California, Contract DACW05-92-P-1983, 1992).

17. Hill, J. M., Singh, V. P. and Aminian, H., "A Computerized Data Base for Flood Prediction Modeling", Water Resources Bulletin, Vol 23(1), 1987, pp. 21-27.

18. Singh, V. P. and Aminian, H., "The Watershed Hydrology Simulation Model", Proceedings of the International Workshop on Operational Applications of Mathematical Models (Surface Water) in Developing Countries, New Delhi, 1985.

19. Al-Smadi, M., "Incorporating Spatial and Temporal Variation of the Watershed Response in a GIS-based Hydrologic Model", (M.S. Thesis, Biological Systems Engineering Department, Virginia Tech., Blacksburg, 1998).

20. Stuebe, M. M. and Johnston, D. M., "Runoff Volume Estimation using GIS Techniques", Water Resources Bulletin, Vol 24(4), 1990, pp. 611-620.

21. Moeller, R. A., " Application of GIS to Hydrologic Modeling using HEC-1", Civil Engineering Applications Remote Sensing and Geographic Information System, edited by Stafford, D. B., New York, ASCE, 1991, pp. 269-277.

22. Bhaskar, N. R., James, W. P. and Devulapalli, R. S., "Hydrologic Parameter Estimation using Geographic Information System", Journal of Water Resources Planning and Management, Vol 118, No. 5, 1992, pp. 492-512.

23. Michelini, M., "Automatic Generation of Unit Hydrograph using Digital Elevation Model" (unpublished M.S. Thesis, School of Engineering, University of Pittsburgh, 1994).

24. Bodnar, R. F., "Verification of Automatically Generated Unit Hydrograph from DEM with field data" (unpublished M.S. Thesis, School of Engineering, University of Pittsburgh, 1995).

25. Zollweg, J. A., Gburek, W. J. and Steenhuis, T. S., "SMoRMod – a GIS integrated Rainfall-runoff Model", Transactions ASAE, Vol 39, No. 4, 1996, pp. 1299-1307.

26. Chow, V.T., Maidment, D. R. and Mays, L. W., Applied Hydrology (McGraw Hill Inc., New York, 1988), pp. 213.

27. Quimpo, R. G., Hydrology and Hydraulics, University of Pittsburgh, 1996.

28. Chow, V.T., Maidment, D. R. and Mays, L. W., Applied Hydrology (McGraw Hill Inc., New York, 1988), pp. 233.

29. Chow, V.T., Maidment, D. R. and Mays, L. W., Applied Hydrology (McGraw Hill Inc., New York, 1988), pp. 10.

30. Dooge, J. C., "Linear Theory of Hydrologic Systems", USDA Technical Bulletin, No. 1468, USDA, Washington DC, 1973.

31. Dooge, J. C., "A General Theory of the Unit Hydrograph", Journal of Geophysical Research, Vol 64, No. 2, 1959, pp. 241-256.

32. Haan, C. T., Barfield, B. J. and Hayes, J. C., Design Hydrology and Sedimentology for Small Catchments (Academic Press, Inc., 1994), pp. 38.

33. "Urban Hydrology for Small Watersheds (TR-55)", Washington DC, USDA, 1986.

REFERENCES NOT CITED

Understanding GIS, The ARC/INFO Method (4th edition; Environmental Systems Research Institute, Inc., 1997).

Eastman, J. R., Idrisi32, Guide to GIS and Image Processing (Volume 1 & 2, Clarks University, 1997).

Kilgore, J. L., "Development and Evaluation of a GIS-based Spatially Distributed Unit Hydrograph Model"(M.S. Thesis, Biological Systems Engineering Department, Virginia Tech., Blackburg, 1997).

Linsley, R. K., Kohler, M. A. and Paulhus , J. L. H., Hydrology for Engineers (McGraw Hill Inc., New York, 1982).

Maidment, D. R., Handbook of Hydrology (McGraw Hill Inc., New York, 1993).

Jenson, S. K. and Domingue, J. O., "Extracting Topological Structure from Digital Elevation Model data for GIS Analysis", Photogrammetric Engineering and Remote Sensing, Vol 54, No. 11, 1988, pp. 1593-1600.